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**Design and simulation of groundwater pumping
systems using variable frequency drives (VFDs)
to enhance water sustainability.**

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إهداء

إلى والديَّ الكريمين،
الذين أضاءت تضحياتُهما وحبُّهما الصادق كلَّ خطوةٍ في مسيرتي.
إلى إخوتي وأخواتي على دعمهم الدائم طوال هذا المسار الدراسي.

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Abstract

Groundwater pumping stations in the Algerian Sahara rely on fixed-speed induction motor drives that impose severe operational constraints: destructive inrush currents at starting, persistent hydraulic mismatch between pump and system characteristics, and energy waste amplified by the cubic relationship between motor speed and shaft power. This thesis investigates the design, simulation, and techno-economic evaluation of a Variable Frequency Drive (VFD) control strategy for the 75 kW submersible pump installation at the University Hub Pumping Station, University Hamma Lakhdar, El Oued, Algeria.

A field diagnostic campaign in March 2026 identified two critical failures in the existing stator-resistance starter: a destructive bypass inrush current of 248 A at the six-second contactor transition, and a chronic hydraulic runout condition at $Q = 150 \text{ m}^3/\text{h}$ (120 % of the Best Efficiency Point flow) that degrades pump efficiency to 73 % and wire-to-water system efficiency to approximately 60 % ($P_{\text{elec}} \approx 59.4 \text{ kW}$).

A MATLAB/Simulink digital twin of the complete motor-inverter-pump system was constructed and validated against the field measurements. Four simulation scenarios comparing the stator-resistance starter with the proposed closed-loop scalar V/f VFD confirm that the VFD eliminates the inrush spike and produces a smooth speed ramp. Reducing the supply frequency from 50 Hz to 44 Hz shifts the operating point to the BEP envelope, recovering pump efficiency to 77.5 %.

The annual energy saving of approximately 141,000 kWh yields a monetary saving of approximately 446,000 DZD/year against Sonelgaz Tariff 42. With a capital expenditure of 955,000 DZD, the simple payback period is approximately 2.1 years, with a strongly positive ten-year NPV of +2,038,000 DZD and an IRR of 45.6 %. The VFD installation is recommended to eliminate mechanical failures, extend pump service life, and support Algeria's water-sector energy efficiency objectives.

Keywords: Variable Frequency Drive (VFD); induction motor; centrifugal pump; scalar V/f control; energy efficiency; water sustainability; MATLAB/Simulink; Oued Souf Valley; Algeria.

ملخص

تعتمد محطات ضخ المياه الجوفية في الصحراء الجزائرية على محركات تحريضية (حثية) ذات سرعة ثابتة، مما يُفرض على قيود تشغيلية صارمة: تيارات إقلاع اندفاعية مدمرة، وعدم تطابق هيدروليكي مزمن بين المضخة والشبكة، وهدر طاقي يتضخم بفعل العلاقة التكميلية بين سرعة المحرك والقدرة المحورية. تتناول هذه المذكرة تصميم وأداء وتقييم تقني-اقتصادي لاستراتيجية التحكم باستخدام مغير التردد (VFD) لمضخة غاطسة بقدرة 75 كيلوواط في محطة ضخ القطب الجامعي، جامعة حمه لخضر، الوادي، الجزائر.

كشفت حملة تشخيص ميداني في مارس 2026 عن خللين حرجين في بادئ التشغيل بمقاومات الجزء الثابت الحالي: تيار إقلاع اندفاعي مدمر بلغ 248 أمبير لحظة تبديل الملامس عند الثانية السادسة، وتشغيل مزمن في حالة التدفق المفرط عند $Q = 150$ م³/ساعة (أي 120% من نقطة الكفاءة المثلى BEP)، مما يدهور كفاءة المضخة إلى 73% وكفاءة النظام الإجمالية من السلك إلى الماء إلى حوالي 60% ($P_{elec} \approx 59.4$ كيلوواط).

تم تطوير توائم رقمي ($MATLAB/Simulink$) للمنظومة الكاملة (محرك - عاكس - مضخة) والتحقق من صحته بالقياسات الميدانية. وتؤكد أربعة سيناريوهات للمحاكاة أن التحكم السلبي المغلق V/f يقضي على ذروة التيار الاندفاعي، وأن خفض تردد التغذية من 50 هرتز إلى 44 هرتز ينقل نقطة التشغيل إلى نطاق الكفاءة المثلى (BEP)، مما يرفع كفاءة المضخة إلى 77.5%.

يُحقق تركيب نظام مغير التردد (VFD) وفورات طاقة سنوية تقارب 141,000 كيلوواط. ساعة، مما يعادل توفيراً مالياً يقارب 446,000 دينار جزائري/سنة وفقاً للتعريف الطاقي 42 لشركة سونلغاز. ومع تكلفة استثمارية تبلغ 955,000 دينار جزائري، فإن فترة الاسترداد البسيطة للمشروع تقدر بـ 2.1 سنة، مع قيمة حالية صافية إيجابية (2,038,000 + دج) ومعدل عائد داخلي قدره 45.6%. يوصى بتركيب مغير التردد (VFD) للقضاء على الأعطال الميكانيكية، وإطالة عمر المضخة، ودعم أهداف كفاءة الطاقة في قطاع المياه بالجزائر.

الكلمات المفتاحية: مغير التردد (VFD)، محرك تحريضي (حثي)، مضخة طاردة مركزية، التحكم السلبي (V/f)، كفاءة الطاقة، الاستدامة المائية، $MATLAB/Simulink$ ، وادي سوف، الجزائر.

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List of Abbreviations

Abbreviation	Definition
AC	Alternating Current
ADE	<i>Algérienne des Eaux</i> (Algerian Water Company)
BEP	Best Efficiency Point
CAPEX	Capital Expenditure
CI	Continental Intercalaire (deep Saharan aquifer layer)
CT	Complexe Terminal (intermediate Saharan aquifer layer)
DC	Direct Current
DCF	Discounted Cash Flow
DOL	Direct-On-Line (motor starting method)
dq	Direct–Quadrature rotating reference frame
DSO	Digital Storage Oscilloscope
EMC	Electromagnetic Compatibility
EMF	Electromotive Force
FOC	Field-Oriented Control
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
IRR	Internal Rate of Return
MATLAB	Matrix Laboratory (MathWorks numerical computing platform)
MCA	<i>Maître de Conférences, Classe A</i> (Associate Professor, Grade A)
MCB	<i>Maître de Conférences, Classe B</i> (Associate Professor, Grade B)
NPSH	Net Positive Suction Head
NPV	Net Present Value
PI	Proportional–Integral (controller)
PID	Proportional–Integral–Derivative (controller)

(continued on next page)

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Abbreviation	Definition
POR	Preferred Operating Region
PWM	Pulse Width Modulation
SCADA	Supervisory Control and Data Acquisition
SEC	Specific Energy Consumption
SPP	Simple Payback Period
SPWM	Sinusoidal Pulse Width Modulation
TDH	Total Dynamic Head
THD	Total Harmonic Distortion
VFD	Variable Frequency Drive
V/f	Voltage-to-Frequency ratio (scalar control law)
VSI	Voltage Source Inverter
VSD	Variable Speed Drive

List of Symbols

Symbol	Description	Unit
η	Efficiency (pump, motor, or system)	—
η_p	Pump hydraulic efficiency	—
η_{mot}	Motor efficiency	—
η_{VFD}	VFD conversion efficiency	—
η_{sys}	Overall wire-to-water efficiency	—
f	Supply frequency	Hz
g	Gravitational acceleration	m/s ²
H	Total dynamic head	m
H_0	Shut-off head (zero-flow)	m
h_f	Friction head loss	m
i_{ds}, i_{qs}	Stator d -axis and q -axis currents	A
i_{dr}, i_{qr}	Rotor d -axis and q -axis currents	A
J	Rotor moment of inertia	kg m ²
k	System resistance coefficient	m/(m ³ /s) ²
k_T	Quadratic torque constant	N m/(rad/s) ²
L_m	Magnetising inductance	H
L_r, L_s	Rotor and stator self-inductances	H
n	Rotational speed	rpm
N_s	Synchronous speed	rpm
P	Active (absorbed or shaft) power	W or kW
P_{hyd}	Hydraulic power	W or kW
Q	Volumetric flow rate	m ³ /s or m ³ /h
R_r, R_s	Rotor and stator resistances	Ω
s	Slip	—
T_{em}	Electromagnetic torque	N m

(continued)

Symbol	Description	Unit
T_L	Load torque	N m
V_t	Stator terminal (phase) voltage	V
Z_g	Geometric (static) head	m
ω	Angular velocity (mechanical)	rad/s
ω_s	Synchronous angular velocity	rad/s
ρ	Fluid density	kg/m ³

Chapter 1

General Introduction

1.1 Introduction to Groundwater Pumping Systems

Groundwater is one of the most important sub-surface freshwater reserves on Earth, providing a reliable buffer against deficient precipitation and depleted surface supplies. Its depth and the natural geological filtration process make it substantially less vulnerable to anthropogenic contamination than open surface bodies [1]. Exploiting this resource requires the strategic drilling of extraction wells positioned in accordance with local hydrogeological surveys, and depends on mechanical pumping units as the primary means of lifting water from deep aquifers to the surface and delivering it under pressure to distribution networks.

An industrial groundwater pumping installation is an integrated electromechanical system that comprises the pump assembly, a piping network, isolation and non-return valves, pressure and flow instrumentation, surge arresters, and storage reservoirs or elevated tanks. The production borehole is drilled and structurally stabilised with steel or polyvinyl chloride (PVC) casing strings [1]. Well depth is governed by aquifer yield characteristics [1], groundwater chemistry [2], and site-specific lithological conditions.

1.2 Groundwater Pumping in the Oued Souf Valley

In the hyper-arid Algerian Sahara, groundwater is the primary source for municipal supply, agriculture, and socio-economic activity. Agricultural expansion accounts for more than two-thirds of total national groundwater withdrawal [3]. In the Oued Souf Valley, in northeastern Algeria, this dependence is total. The regional aquifer system comprises three superimposed layers: the superficial Phreatic aquifer, the Intermediate Complex Terminal (CT), and the deep Continental Intercalary (CI) [4]. Continuous operation of electric submersible and vertical-turbine pumps at these wells sustains regional water security.

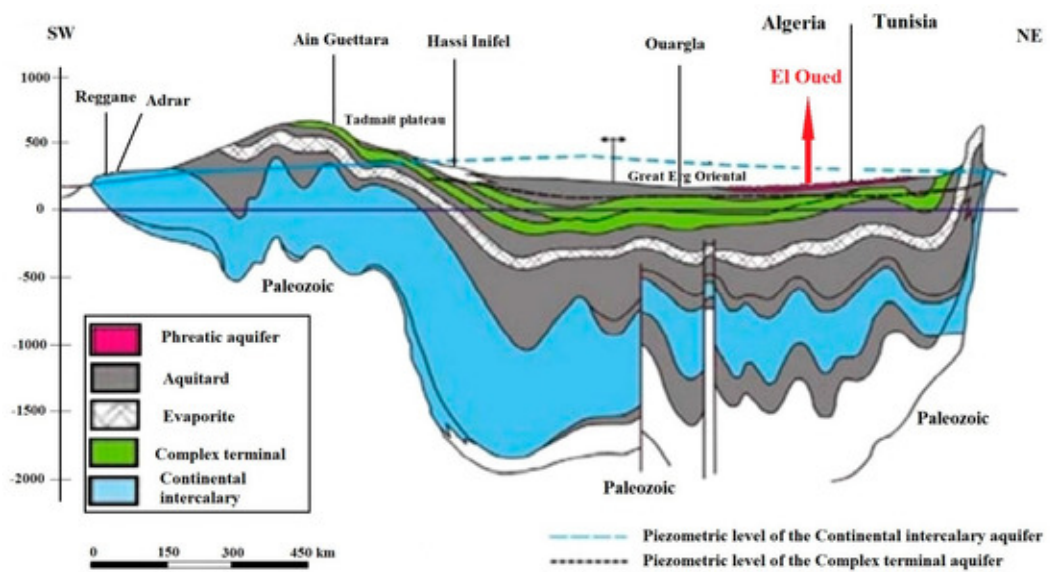


Figure 1.1: Hydrogeological cross-section of the multi-layered Saharan aquifer system of the Oued Souf basin [4].

Unmanaged extraction has caused severe hydrogeological and engineering problems. Uncontrolled pumping rates produce large temporal variations and localised water-table shifts, including the historically documented rise of the water table in the low-lying *chotts* of El Oued [4]. From an engineering standpoint, the aggressive operational regime subjects submersible infrastructure to sand abrasion, chemical corrosion from mineralised formation water, and grid voltage fluctuations typical of remote desert stations [5]. These conditions accelerate degradation and recurrent pump failures, making the transition from fixed-speed starting methods to Variable Frequency Drive (VFD) control both necessary and urgent.

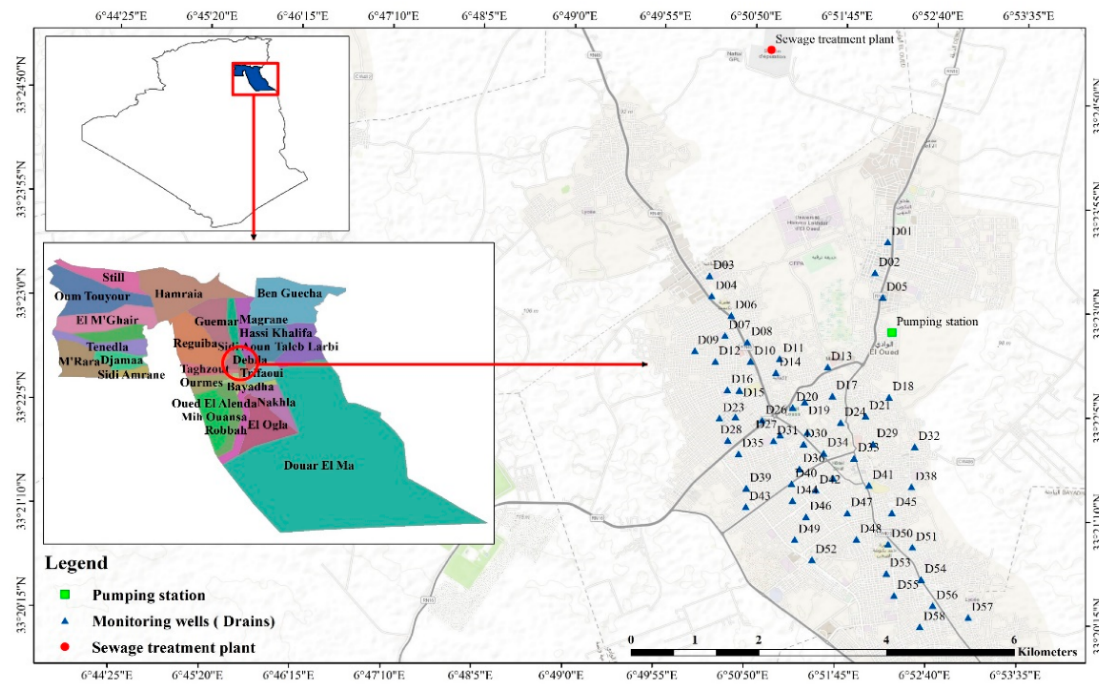


Figure 1.2: Geographic distribution of hydraulic pumping infrastructure and groundwater monitoring wells in the Oued Souf region [4, 5].

1.3 Centrifugal Pumping and Energy Efficiency

Hydraulic pumps transfer fluids from low-pressure zones to high-pressure zones or raise liquids across topographic differences. Among industrial pump types, centrifugal submersible pumps are the dominant choice for deep-well groundwater extraction, closed thermal circuits, and municipal wastewater management [6]. A centrifugal pump converts the mechanical energy supplied by the motor into kinetic energy through a rotating impeller; fluid enters axially at the impeller eye, accelerates radially along the backward-curved vanes, and the resulting kinetic energy is recovered as static pressure in the volute casing.

Pumping systems account for approximately 20% of the world's total electrical energy demand and between 25–50% of total operational energy consumption in water treatment and supply plants [2]. Oversized or fixed-speed pumps operating away from their Best Efficiency Point (BEP) waste considerable electrical energy. Historically, water networks have relied on pressure-reducing valves (PRVs) and throttling valves to manage variable hydraulic demand [7]. Throttling forces the system to operate against artificial hydraulic resistance, dissipating energy as heat and friction, and increasing the risk of pipeline failures and leakage. Replacing throttling control with automated VFD speed regulation eliminates these losses and improves long-term infrastructure reliability.

1.4 Electromechanical Dynamics of Induction Motors

Three-phase AC induction motors are the primary drivers of industrial centrifugal pumps [8]. More than half of global industrial electrical energy is converted to mechanical energy through AC induction motors, which are deployed in pumps, fans, compressors, mixers, conveyors, and machine tools. Coupling squirrel-cage induction motors with static variable frequency converters for variable speed drive (VSD) applications has become standard practice in industrial automation [9]. This integration enables dynamic torque regulation and fluid velocity adaptation. To understand and quantify how a VFD reshapes motor performance, it is necessary to understand the electromagnetic operating principles, rotor-stator slip dynamics, and flux configurations that govern this class of electrical machine [8].

1.5 Variable Speed Drive Topologies

The growing adoption of Variable Speed Drives (VSDs) in groundwater pumping is driven by the potential for electrical energy savings and improved operational flexibility. When a VFD is coupled to a submersible centrifugal pump, the inverter continuously adjusts motor speed to match a real-time process setpoint, aligning the hydraulic flow rate with instantaneous demand or well safe-yield [9]. This regulation reduces power consumption and mechanical stress. The principal advantages of VSD integration in hydraulic systems include [9]:

- **Speed matched to demand:** Motor synchronous speed is adjusted continuously to match the required hydraulic head and flow rate, eliminating energy lost through mechanical throttling valves.
- **Optimised torque profile:** Electromagnetic torque is adapted to the quadratic load characteristic of centrifugal machinery, ensuring stable and efficient part-load operation.
- **Cubic power reduction:** Specific energy consumption (SEC) is substantially reduced by exploiting the cubic relationship between pump speed and absorbed power defined by the hydraulic affinity laws.

1.6 Problem Statement

Groundwater pumping systems face compounding operational challenges: seasonal aquifer-level fluctuations, prolonged droughts, energy inefficiencies, and the continuous need for infrastructure optimisation. The motor-drive subsystem represents the largest single energy consumer at any pumping station; reducing its specific energy consumption is therefore the central step toward ensuring water sustainability.

At the University Campus Pumping Station in El Oued, the system currently relies on an outdated fixed-speed stator resistor starter driving a 75 kW submersible induction motor. When water demand or aquifer levels vary, the system cannot adapt dynamically. Declining groundwater levels during peak demand seasons reduce actual output capacity and force the pump into repeated on-off cycling, which imposes severe electrical and mechanical stress on the motor, causing frequent failures and high maintenance costs. Operating at constant rated speed, the motor draws near-rated power regardless of actual hydraulic demand — a direct and quantifiable energy waste.

Implementing a closed-loop VFD control system offers a technically and economically sound solution. By adjusting motor speed continuously in response to real-time hydraulic conditions, such a system eliminates energy waste, prevents destructive cycling, and improves the sustainability of the campus water supply.

1.7 Objectives

1.7.1 General Objective

The general objective of this thesis is to evaluate the operational performance of the University Campus Pumping Station in El Oued, improve its energy efficiency, and assess the economic viability of replacing the existing fixed-speed stator resistor starter with a closed-loop VFD control system for the 75 kW submersible induction motor. The goals are to optimise energy consumption, eliminate motor cycling caused by aquifer-level fluctuations, and enhance the long-term sustainability of the campus water supply.

1.7.2 Specific Objectives

To achieve this general objective, the following specific tasks are addressed:

1. **Collect and review technical data.** Gather design documents, manufacturer data sheets, and pump performance curves for the 75 kW submersible pump motor at the University Campus Pumping Station.
2. **Assess baseline efficiency.** Evaluate current fixed-speed operation under the stator resistor starter and quantify its deviation from the pump's Best Efficiency Point (BEP).
3. **Monitor operational and environmental variations.** Collect field data on groundwater level fluctuations, their effect on actual flow rates, and the resulting on-off cycling behaviour of the motor.
4. **Quantify energy waste.** Evaluate how fixed-speed operation affects mechanical and electrical efficiency, and quantify the resulting energy losses and mechanical stress on the motor.

5. **Develop MATLAB/Simulink models.** Build a mathematical and simulation model of the induction motor and pumping system in MATLAB/Simulink to study dynamic behaviour under both operating modes.
6. **Design the closed-loop VFD controller.** Design and simulate a closed-loop VFD system based on the constant V/f scalar control strategy, dynamically regulating motor speed according to real-time hydraulic demand and water-level signals.
7. **Perform techno-economic evaluation.** Conduct a financial and technical audit quantifying annual energy savings, maintenance cost reductions, and motor lifespan extension attributable to VFD implementation.
8. **Formulate recommendations.** Provide technical conclusions and site-specific recommendations for improving energy efficiency and ensuring water sustainability at the University Campus Pumping Station.

1.8 Scope of the Thesis

The scope of this research is defined by the technical, operational, and geographical boundaries of the University Campus Pumping Station in El Oued, Algeria. The empirical data are provided by the Algerian Water Company (*Algérienne des Eaux* — ADE, El Oued), supplemented by direct field measurements recorded at the station by the author.

Geographically, the study is confined to a single deep groundwater well equipped with a 75 kW submersible induction motor delivering water to an elevated storage tank. While essential hydraulic parameters such as flow rate and system pressure are incorporated, the core focus lies within the electrical control specialisation: electromechanical modelling, VFD design, and closed-loop control. The proposed system replaces the stator resistor starter with a closed-loop VFD operating under the constant V/f scalar control strategy, with feedback based on volumetric flow rate and line pressure. All modelling, simulation, and performance evaluation are carried out exclusively in the MATLAB/Simulink environment. The scope also includes a techno-economic analysis quantifying annual electricity savings, maintenance cost reductions, and the financial payback period of the proposed upgrade.

The remainder of this thesis is organised as follows. Chapter 2 reviews the theoretical foundations of centrifugal pumping systems and energy optimisation: total dynamic head, system and pump curves, hydraulic affinity laws, wire-to-water efficiency, specific energy consumption, and the operating principles of motor starting methods and VFD scalar control. Chapter 3 presents the MATLAB/Simulink modelling and simulation of the complete motor–inverter–pump system, including the d - q state-space induction motor model, the three-phase VSI, and the closed-loop V/f controller, and compares four simulation scenarios between

stator-resistance starting and VFD control. Chapter 4 reports the field diagnosis and performance evaluation campaign conducted at the University Hub Pumping Station, El Oued, documenting the measured electrical and hydraulic parameters and identifying the chronic hydraulic mismatch. Chapter 5 carries out the VFD system design and techno-economic evaluation, applying the affinity law analysis to quantify energy savings, monetary benefits, and the payback period. A general conclusion summarises the main findings and outlines directions for future work.

Chapter 2

Pumping System Energy Optimisation

This chapter establishes the theoretical foundations required for the design and simulation presented in subsequent chapters. Sections 2.1 and 2.2 cover the hydraulic principles governing centrifugal pumping systems, including the total dynamic head, affinity laws, efficiency metrics, and net positive suction head. Section 2.3 develops the mathematical model of the three-phase induction motor in the synchronously rotating d - q reference frame. Section 2.4 details the Voltage Source Inverter (VSI) topology and Pulse Width Modulation (PWM) switching equations. Section 2.5 compares the two motor starting strategies evaluated in this work: the stator resistance starter and the closed-loop scalar V/f VFD controller.

2.1 Fundamental Components of Water Pumping Systems

Evaluating a water pumping system requires analysis of the entire electro-hydraulic chain, not only the pump itself [1]. A groundwater pumping installation for elevated reservoir storage comprises the submersible pump unit, suction and delivery piping, isolation and non-return valves, pressure and flow instrumentation, surge arresters, and a storage reservoir or elevated tank.

To sustain the required flow rate, the pump must overcome the Total Dynamic Head (TDH), which combines two components. The *static head* (H_{st}) is the net vertical displacement between the suction water level and the delivery point, plus any pressure differential between source and destination. The *dynamic head* (H_{dyn}) represents energy dissipated by friction in pipes, valves, and fittings [1]. In deep-well applications, the static lift dominates energy consumption and makes precise speed control essential for efficiency.

Figure 2.1 shows a typical groundwater pumping installation with its principal hydraulic and electrical subsystems.

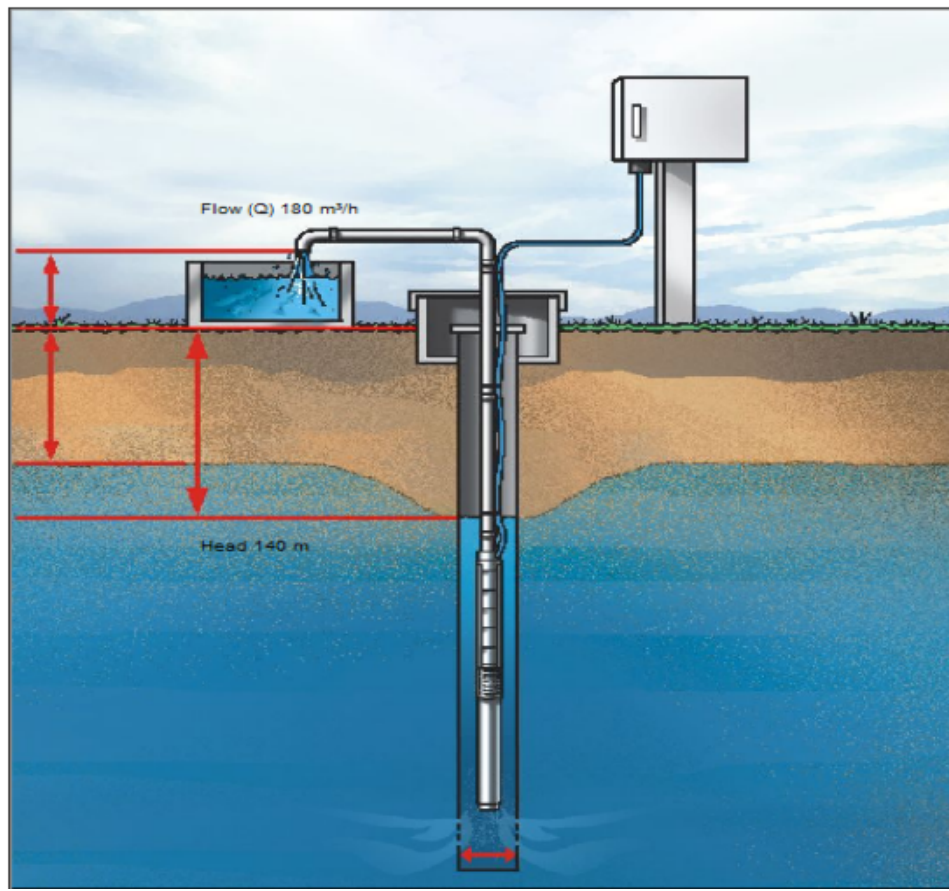


Figure 2.1: Schematic of a groundwater pumping installation showing the principal hydraulic and electrical subsystems [1].

2.2 Fundamental Theory of Centrifugal Pumping

Industrial pumps are classified as kinetic or positive-displacement. The centrifugal pump — the dominant kinetic type in water supply — comprises a hydraulic assembly (wet end) and a mechanical drive end. Fluid enters the impeller axially at the eye, is accelerated radially along the backward-curved vanes by centrifugal force, and the resulting kinetic energy is recovered as static pressure in the volute casing. For a given impeller geometry and constant speed, the energy imparted per unit weight of fluid is independent of fluid density, determining the hydraulic head produced [10].

2.2.1 Flow, Head, and Efficiency

The performance of a pumping system is governed by two primary variables: the volumetric flow rate Q (m^3/h or L/s) and the total dynamic head H (m) [2, 6].

Total Dynamic Head

The total head is the energy per unit weight imparted to the fluid, expressed by the extended Bernoulli equation between suction inlet (e) and discharge outlet (a) [1]:

$$H = H_{\text{geo}} + \frac{P_a - P_e}{\rho g} + \frac{V_a^2 - V_e^2}{2g} + \sum_{i=1}^n H_{r,i} \quad (2.1)$$

where H is the total dynamic head (m); H_{geo} is the geodetic elevation difference (m); P_a , P_e are absolute pressures at outlet and inlet (Pa); V_a , V_e are fluid velocities at outlet and inlet (m/s); $H_{r,i}$ are head losses due to friction (m); ρ is fluid density (kg/m³); $g = 9.81$ m/s².

The static component combines the elevation difference and the pressure differential:

$$H_{\text{st}} = H_{\text{geo}} + \frac{P_a - P_e}{\rho g} \quad (2.2)$$

The dynamic component accounts for friction losses and the kinetic energy change:

$$H_{\text{dyn}} = \sum_{i=1}^n H_{r,i} + \frac{V_a^2 - V_e^2}{2g} \quad (2.3)$$

In open-loop groundwater systems the pressure differential in (2.2) is negligible (open-air suction and discharge), and the velocity head in (2.3) is small relative to the total head. Friction losses are proportional to the square of the flow rate [11]:

$$H_{\text{dyn}} = kQ^2 \quad (2.4)$$

where k is the hydraulic resistance coefficient of the piping network (m/(m³/h)²).

Combining (2.2) and (2.4) gives the *system head curve*, the fundamental design equation for pump-system matching [11]:

$$\boxed{H = H_{\text{st}} + kQ^2} \quad (2.5)$$

The system head curve is plotted on the Q - H plane and intersects the pump's performance curve at the *operating point*. Maximum efficiency is achieved when this intersection coincides with the pump's Best Efficiency Point (BEP). Figure 2.2 illustrates the system head curve and its intersection with a family of pump curves at different speeds.

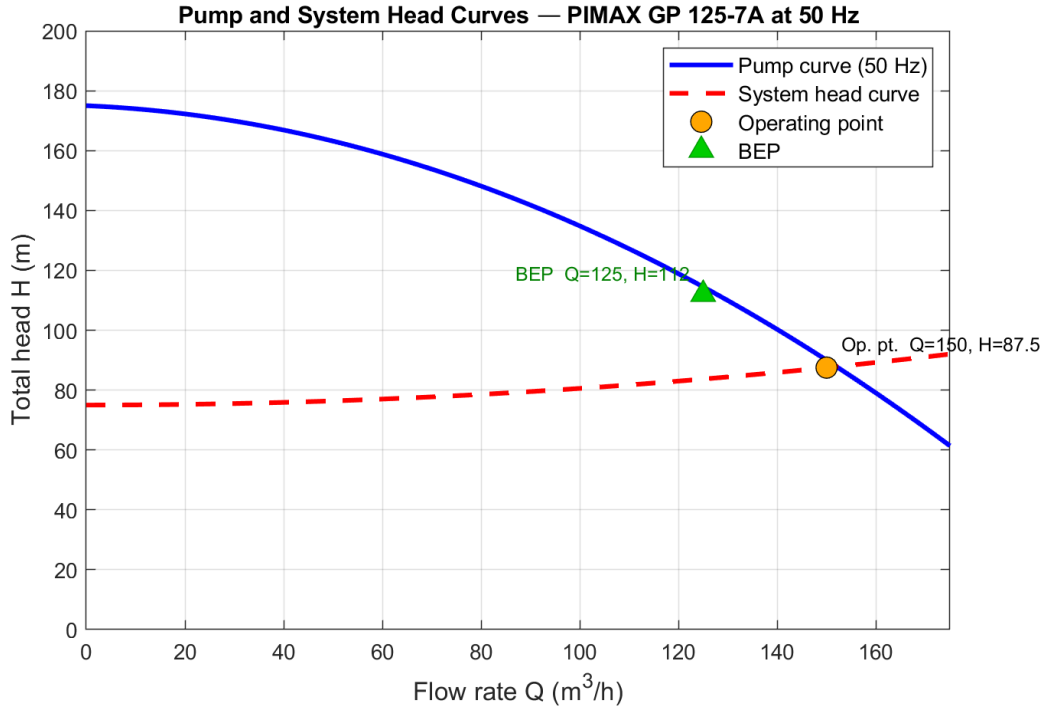


Figure 2.2: System head curve $H_{\text{sys}} = H_{\text{st}} + kQ^2$ and pump Q - H characteristic at 50 Hz for the PIMAX GP 125-7A, showing the current operating point ($Q = 150 \text{ m}^3/\text{h}$, $H = 87.5 \text{ m}$) and the Best Efficiency Point ($Q_{\text{BEP}} = 125 \text{ m}^3/\text{h}$, $H_{\text{BEP}} = 112 \text{ m}$) [1].

Pump and System Efficiency

The total intrinsic pump efficiency η_p is the product of its hydraulic, volumetric, and mechanical component efficiencies [1, 11]:

$$\eta_p = \eta_h \cdot \eta_v \cdot \eta_m \quad (2.6)$$

The overall wire-to-water efficiency η_{sys} extends this to include the electric drive [10, 11]:

$$\eta_{\text{sys}} = \eta_p \cdot \eta_d = \eta_h \cdot \eta_v \cdot \eta_m \cdot \eta_d \quad (2.7)$$

where η_h , η_v , η_m are the hydraulic, volumetric, and mechanical efficiencies of the pump; η_d is the drive (motor + VFD) efficiency.

2.2.2 Rotational Speed, Power, and VFD Integration

Hydraulic and Shaft Power

The hydraulic power delivered to the fluid, with Q in m^3/h , is:

$$P_{\text{hyd}} = \frac{\rho g Q H}{3.6 \times 10^6} \quad (2.8)$$

where P_{hyd} is hydraulic power (kW); Q is volumetric flow rate (m³/h); H is total dynamic head (m).

The shaft (absorbed) power accounts for internal losses via the pump efficiency:

$$P_a = \frac{\rho g Q H}{1000 \eta_p} \quad (2.9)$$

Synchronous Speed and Slip

For a fixed-frequency grid supply, the synchronous speed of a three-phase induction motor is:

$$N_s = \frac{60 f}{p} \quad (2.10)$$

where N_s is synchronous speed (rpm); f is supply frequency (Hz); p is the number of pole pairs.

Due to induction motor slip, the actual rotor speed $N < N_s$. The slip is defined as [8]:

$$s = \frac{N_s - N}{N_s} \quad (2.11)$$

A VFD decouples the motor from the grid frequency by continuously adjusting the stator supply frequency f , enabling precise speed regulation and eliminating the rigid N_s constraint [10].

Specific Energy Consumption

The Specific Energy Consumption (SEC) quantifies the electrical energy drawn per unit volume of water delivered [12]:

$$\text{SEC} = \frac{P_{\text{elec}} t}{V_{\text{total}}} = \frac{P_{\text{elec}}}{Q} = \frac{\rho g H}{3.6 \times 10^6 \eta_{\text{sys}}} \quad (2.12)$$

where SEC has units of kWh/m³; P_{elec} is active electrical input power (kW); t is pumping duration (h); V_{total} is total volume pumped (m³).

In systems dominated by static head (deep wells), the minimum achievable SEC is bounded by the geodetic lift and fluid properties. In friction-dominated systems, VFD speed control tracks the minimum SEC profile by shifting the operating point along the system curve [12].

2.2.3 Affinity Laws

The hydraulic affinity laws (similarity laws) define the scaling of pump performance when rotational speed changes at constant impeller diameter [10]. They are the primary justification

for VFD control in centrifugal pumping applications.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \quad (2.13)$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1} \right)^2 \quad (2.14)$$

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1} \right)^3 \quad (2.15)$$

$$\frac{\text{NPSH}_{r,2}}{\text{NPSH}_{r,1}} = \left(\frac{N_2}{N_1} \right)^2 \quad (2.16)$$

where subscripts 1 and 2 denote operating conditions at speeds N_1 and N_2 respectively.

The cubic power law in (2.15) is the key energy argument for VFD use: reducing pump speed to 80 % of nominal ($N_2/N_1 = 0.8$) reduces flow to 80 %, head to 64 %, and absorbed power to only $0.8^3 = 51.2\%$ — a 48.8 % power saving compared to throttle control at full speed [10].

Figure 2.3 shows the resulting family of Q - H curves at different speeds.

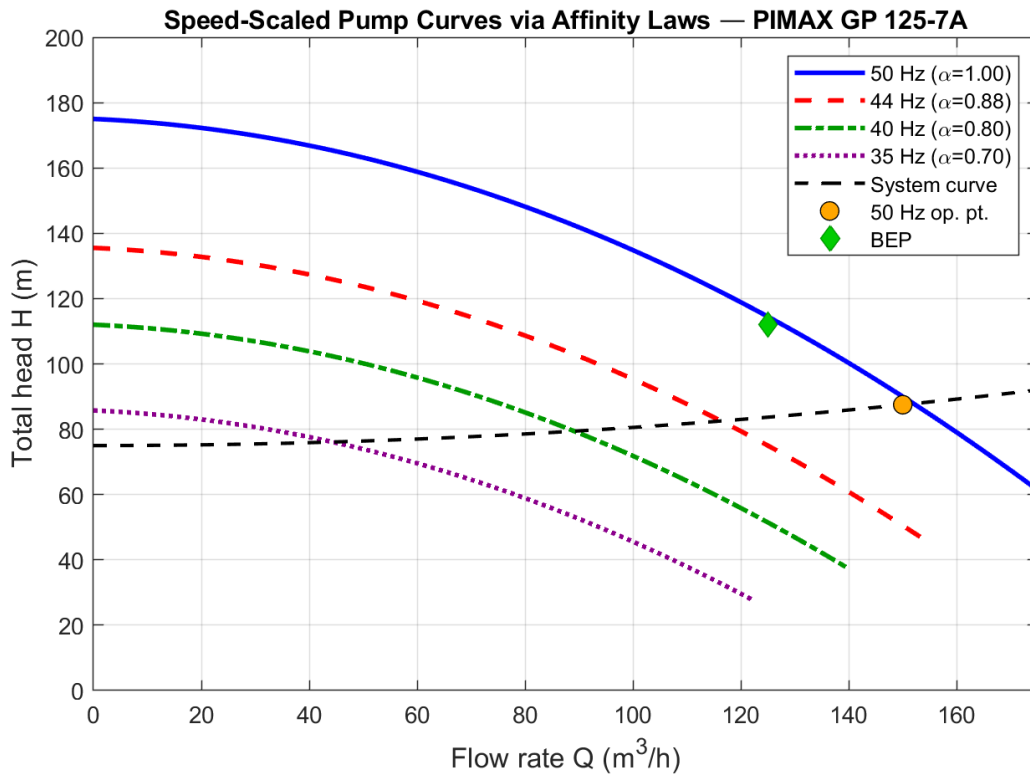


Figure 2.3: Family of centrifugal pump Q - H curves at 50 Hz, 44 Hz, 40 Hz, and 35 Hz, derived from the nominal polynomial by the affinity laws (equation (2.13)–(2.14)), overlaid with the system head curve [10].

2.2.4 NPSH and Cavitation

Net Positive Suction Head (NPSH) quantifies the margin by which the total absolute pressure at the pump suction nozzle exceeds the vapour pressure of the pumped fluid at operating temperature [1, 6]. Two values are distinguished:

- NPSH_a — *available* NPSH: a site characteristic determined by the suction piping geometry and barometric conditions.
- NPSH_r — *required* NPSH: a pump characteristic specified by the manufacturer; the minimum pressure needed at the impeller eye to prevent vapour formation.

The cavitation-free operating condition is [11]:

$$\text{NPSH}_a > \text{NPSH}_r \quad (2.17)$$

Industrial practice requires an additional safety margin of at least 0.5 m [11]:

$$\text{NPSH}_a > \text{NPSH}_r + 0.5 \quad (2.18)$$

The available NPSH is evaluated from suction-side energy parameters:

$$\text{NPSH}_a = \frac{p_e + p_b - p_v}{\rho g} + \frac{v_e^2}{2g} - H_{v,s} \pm H_{\text{geo},s} \quad (2.19)$$

where p_e is gauge pressure at the free suction surface (Pa); p_b is atmospheric (barometric) pressure (Pa); p_v is vapour pressure at operating temperature (Pa); v_e is velocity at the suction nozzle (m/s); $H_{v,s}$ is total friction loss in the suction piping (m); $H_{\text{geo},s}$ is geodetic suction height (positive for flooded suction, negative for suction lift).

Cavitation occurs when local static pressure at the impeller falls below p_v . Vapour bubbles form and then collapse violently as they move into higher-pressure zones, causing erosive pitting of the impeller, loss of head, reduced efficiency, and severe vibration [1].

2.3 Induction Motor Electromechanical Model

The three-phase induction motor drives the centrifugal pump and is the primary energy-consuming element in the pumping station [8]. To design and simulate the VFD control system, an accurate dynamic model of the motor is required. The model is developed in the synchronously rotating d - q reference frame using Park's power-invariant transformation, which converts the time-varying inductances of the natural (abc) frame into constant parameters [13].

2.3.1 d - q Reference Frame Transformation

Natural-Frame Voltage Equations

In the natural abc reference frame, the stator and rotor voltage equations are [13]:

$$\mathbf{v}_{abc,s} = R_s \mathbf{i}_{abc,s} + \frac{d}{dt} [\boldsymbol{\lambda}_{abc,s}] \quad (2.20)$$

$$\mathbf{v}_{abc,r} = R_r \mathbf{i}_{abc,r} + \frac{d}{dt} [\boldsymbol{\lambda}_{abc,r}] \quad (2.21)$$

The flux linkages contain the rotor-angle-dependent mutual inductance matrix $[L_{sr}(\theta_r)]$ [13, 14]:

$$[L_{sr}(\theta_r)] = L_m \begin{bmatrix} \cos \theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos \theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos \theta_r \end{bmatrix} \quad (2.22)$$

where L_m is the peak mutual inductance; θ_r is the instantaneous electrical rotor angle.

Because $[L_{sr}(\theta_r)]$ is time-varying and non-linear, direct simulation of these equations is impractical. Park's transformation eliminates this dependence.

Power-Invariant Park's Transformation

The power-invariant (orthonormal) transformation matrix that maps three-phase quantities onto the arbitrary $dq0$ frame is [13, 15]:

$$[T(\theta)] = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2.23)$$

where θ is the instantaneous angular position of the rotating frame relative to the stationary a -axis.

Figure 2.4 illustrates the geometric relationship between the stationary abc axes and the rotating dq frame.

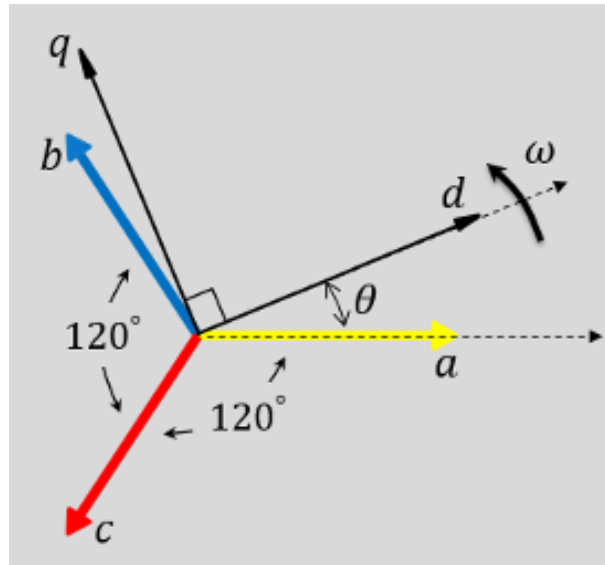


Figure 2.4: Coordinate transformation from the stationary three-phase abc frame to the synchronously rotating dq reference frame [13].

Synchronous Reference Frame Selection

For scalar V/f control, the *synchronously rotating* frame is used: the dq axes rotate at the stator supply angular frequency ω_s . The frame angle is obtained by integrating the synchronous speed:

$$\theta_s = \int \omega_s dt \quad (2.24)$$

The slip angular speed relates the synchronous and electrical rotor speeds [14]:

$$\omega_{sl} = \omega_s - \omega_r \quad (2.25)$$

Under balanced steady-state conditions, all sinusoidal stator variables become DC quantities in the synchronous frame, simplifying control loop design.

2.3.2 State-Space Equations in the d - q Frame

Voltage Equations

Applying the transformation (2.23) with $\theta = \theta_s$ to (2.20)–(2.21) yields four first-order differential equations [13, 14]:

$$V_{ds} = R_s I_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \quad (2.26)$$

$$V_{qs} = R_s I_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \quad (2.27)$$

$$0 = R_r I_{dr} + \frac{d\lambda_{dr}}{dt} - \omega_{sl} \lambda_{qr} \quad (2.28)$$

$$0 = R_r I_{qr} + \frac{d\lambda_{qr}}{dt} + \omega_{sl} \lambda_{dr} \quad (2.29)$$

where V_{ds} , V_{qs} are stator d - and q -axis voltages (V); I_{ds} , I_{qs} , I_{dr} , I_{qr} are stator and rotor d/q -axis currents (A); λ_{ds} , λ_{qs} , λ_{dr} , λ_{qr} are flux linkages (Wb); R_s , R_r are stator and rotor resistances (Ω); rotor voltages are zero for a squirrel-cage motor.

Flux Linkage Equations

With the power-invariant transformation, all trigonometric position-dependence is eliminated. The flux-current relations become constant [13]:

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (2.30)$$

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (2.31)$$

$$\lambda_{dr} = L_r I_{dr} + L_m I_{ds} \quad (2.32)$$

$$\lambda_{qr} = L_r I_{qr} + L_m I_{qs} \quad (2.33)$$

where $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$ are total stator and rotor self-inductances (H); L_{ls} , L_{lr} are leakage inductances; L_m is the magnetising inductance.

Electromagnetic Torque

Under the power-invariant transformation, the electromagnetic torque is:

$$T_{em} = p(\lambda_{ds} I_{qs} - \lambda_{qs} I_{ds}) \quad (2.34)$$

where T_{em} is electromagnetic torque (N m); p is the number of pole pairs.

Mechanical Dynamic Equation

The electromechanical coupling between the motor and the pump is governed by Newton's second law for rotating systems [14]:

$$T_{em} - T_L = J \frac{d\Omega_m}{dt} + B\Omega_m \quad (2.35)$$

where J is the combined moment of inertia of motor rotor and pump impeller (kg m^2); B is the viscous friction coefficient (N m s/rad); Ω_m is mechanical rotor speed (rad/s); T_L is load torque (N m).

For a centrifugal pump, the load torque follows the quadratic speed law [1]:

$$T_L = k_p \Omega_m^2 \quad (2.36)$$

where k_p is the pump torque constant ($\text{N m s}^2/\text{rad}^2$).

Matrix State-Space Form

For MATLAB/Simulink implementation, the dq equations are arranged into a compact matrix state-space form by substituting the flux-current relations into the voltage equations [13, 14]:

$$\mathbf{V} = [R]\mathbf{I} + [L]\dot{\mathbf{I}} + \omega_s[A_1]\mathbf{I} + \omega_{sl}[A_2]\mathbf{I} \quad (2.37)$$

where $\mathbf{V} = [V_{ds}, V_{qs}, 0, 0]^\top$; $\mathbf{I} = [I_{ds}, I_{qs}, I_{dr}, I_{qr}]^\top$; $[R]$ and $[L]$ are the resistance and inductance matrices; $[A_1]$, $[A_2]$ are cross-coupling rotational matrices containing L_s , L_r , and L_m .

Solving for the current derivative:

$$\dot{\mathbf{I}} = [L]^{-1}(\mathbf{V} - [R]\mathbf{I} - \omega_s[A_1]\mathbf{I} - \omega_{sl}[A_2]\mathbf{I}) \quad (2.38)$$

This form avoids algebraic loops in Simulink by selecting flux linkages as state variables, integrating them, and then computing currents algebraically from the inverse inductance matrix $[L]^{-1}$.

2.3.3 Torque-Speed Characteristics and Load Profiles

The induction motor speed is inherently tied to the mechanical load profile. At steady state, $T_{em} = T_L$. The dynamic stability of the drive system depends on how the motor and load torque-speed curves interact [16].

Industrial mechanical loads are classified into four torque profiles:

1. **Constant torque, variable speed:** torque is independent of speed; power increases linearly with speed. Typical examples: positive displacement pumps, conveyors, hoists.

2. **Quadratic (variable) torque:** $T_L \propto \Omega^2$, power $\propto \Omega^3$. This is the dominant profile in centrifugal pumps and fans, and the primary motivation for VFD control (see (2.36) and (2.15)).
3. **Constant power:** torque varies inversely with speed ($T_L \propto 1/\Omega$). Typical examples: winders, metal-cutting lathes.
4. **Composite (constant torque + constant power):** the load operates at constant torque up to a base speed, then at constant power above it.

Figure 2.5 illustrates the speed-torque-power characteristics of each profile.

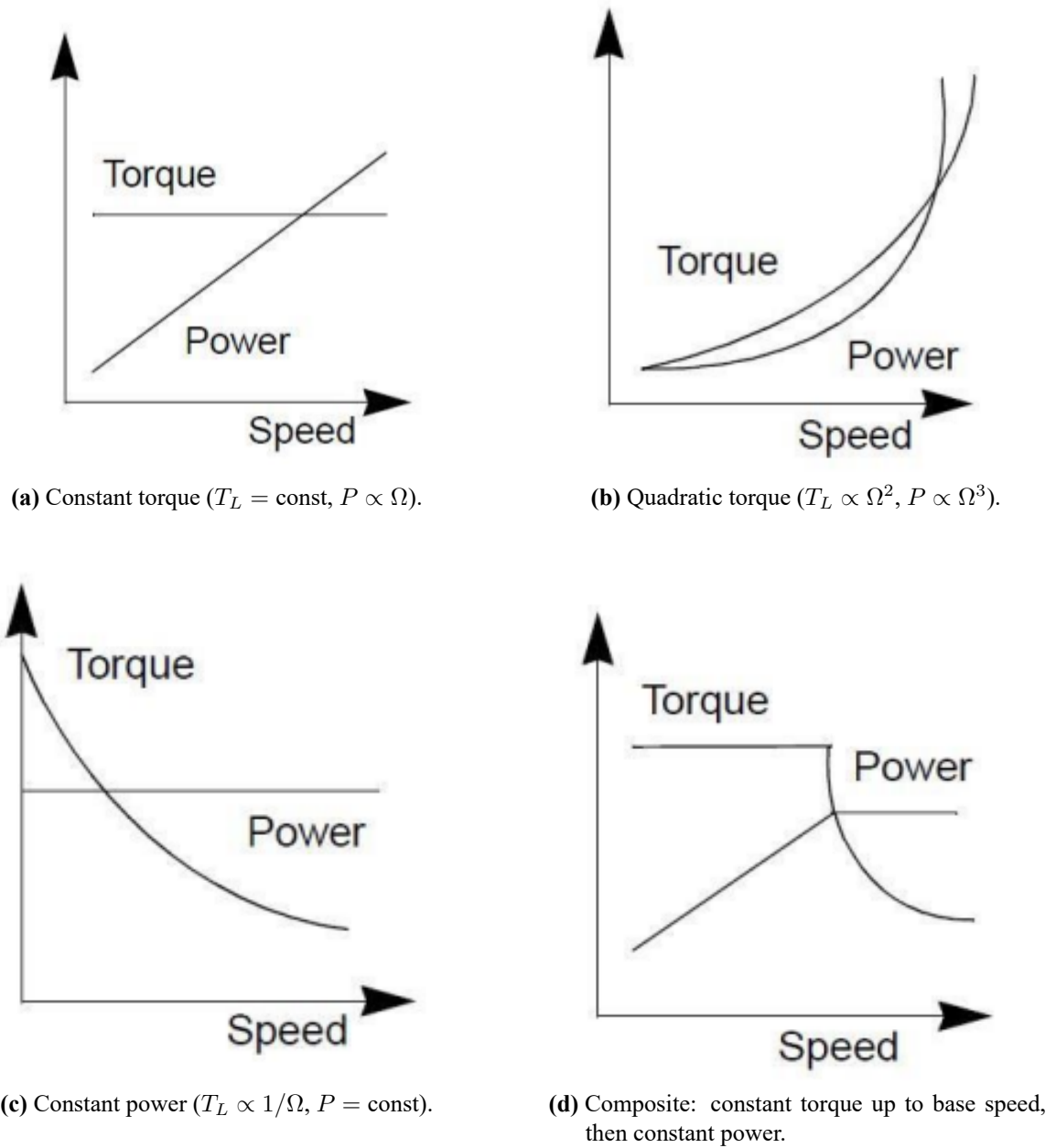


Figure 2.5: Torque-speed and power-speed load characteristic profiles for the four major industrial drive categories [16]. The centrifugal pump belongs to the quadratic-torque class (b), making it the prime beneficiary of VFD speed reduction via the cubic power law $P \propto \Omega^3$.

2.4 Three-Phase Voltage Source Inverter and PWM

The Voltage Source Inverter (VSI) is the power electronics stage of the VFD. It converts the regulated DC-link voltage V_{dc} into a variable-voltage, variable-frequency three-phase AC output that drives the induction motor stator [12, 17].

The standard VSI topology uses six Insulated Gate Bipolar Transistors (IGBTs) arranged in three half-bridge legs (phases a , b , c), each with an anti-parallel freewheeling diode that

provides a safe path for inductive stator current during switch turn-off, preventing destructive voltage spikes. Figure 2.6 shows the circuit topology.

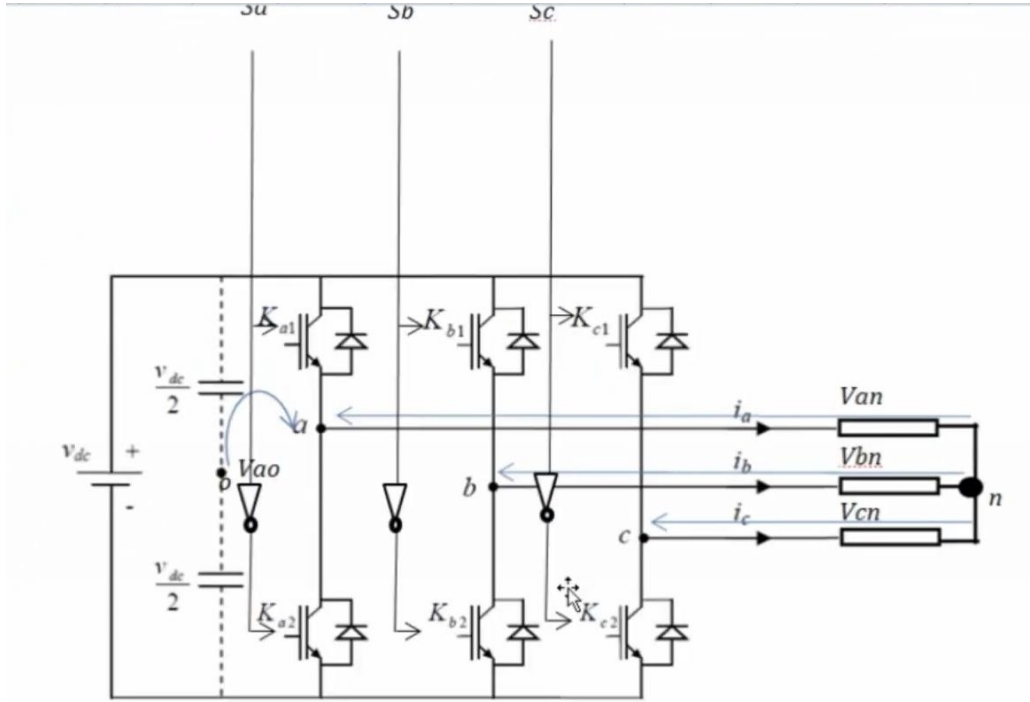


Figure 2.6: Standard three-phase Voltage Source Inverter (VSI) circuit topology with six IGBT switches T_1 – T_6 and anti-parallel freewheeling diodes arranged in three half-bridge legs across the DC-link capacitor bank.

2.4.1 SPWM Switching Logic

Sinusoidal Pulse Width Modulation (SPWM) is the standard technique for controlling the VSI output voltage. Three sinusoidal reference signals $v_{ref,a}$, $v_{ref,b}$, $v_{ref,c}$ — phase-shifted by 120° and at the desired fundamental frequency f_s — are compared against a common high-frequency triangular carrier signal v_{tri} at the switching frequency f_{sw} [12, 17]:

- If $v_{ref,k} > v_{tri}$: the upper switch of leg k is turned ON ($S_k = 1$).
- If $v_{ref,k} \leq v_{tri}$: the lower switch of leg k is turned ON ($S_k = 0$).

The amplitude modulation index $m_a = \hat{V}_{ref}/\hat{V}_{tri}$ controls the output voltage magnitude; the frequency ratio $m_f = f_{sw}/f_s$ controls the harmonic spectrum. Varying m_a and f_s simultaneously according to a constant V/f law (see Section 2.5.2) maintains rated air-gap flux across the full speed range [14].

Figure 2.7 shows the functional block diagram of the complete VFD power stage.

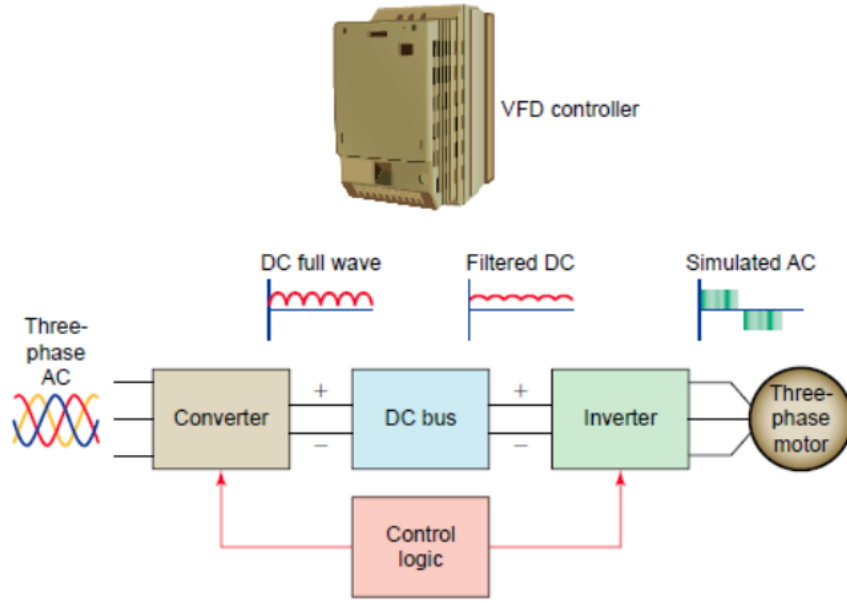


Figure 2.7: Functional block diagram of a three-phase VFD: rectifier stage, DC-bus capacitor filter, IGBT inverter stage, and SPWM control logic [8].

2.4.2 Switching Functions and Output Voltages

The switching state of each inverter leg is described by a binary function S_k ($k \in \{a, b, c\}$) [12, 17]:

$$S_k = \begin{cases} 1 & \text{upper switch } K_{k1} \text{ ON, lower } K_{k2} \text{ OFF} \\ 0 & \text{upper switch } K_{k1} \text{ OFF, lower } K_{k2} \text{ ON} \end{cases} \quad (2.39)$$

Upper and lower switches of the same leg are complementary ($K_{k1} \text{ ON} \Rightarrow K_{k2} \text{ OFF}$) to prevent a DC-bus short-circuit. For simulation efficiency, unipolar states $S_k \in \{0, 1\}$ are mapped to bipolar states $K_k \in \{-1, +1\}$ via $K_k = 2S_k - 1$, giving the pole voltages:

$$V_{ao} = K_a \frac{V_{dc}}{2}, \quad V_{bo} = K_b \frac{V_{dc}}{2}, \quad V_{co} = K_c \frac{V_{dc}}{2} \quad (2.40)$$

where V_{ao} , V_{bo} , V_{co} are pole voltages relative to the DC-bus midpoint o .

For a balanced three-phase motor load, $V_{an} + V_{bn} + V_{cn} = 0$, from which the neutral-to-midpoint voltage is:

$$V_{on} = -\frac{1}{3} (V_{ao} + V_{bo} + V_{co}) \quad (2.41)$$

Substituting (2.40) and (2.41) gives the phase-to-neutral voltages delivered to the motor stator as a single matrix equation [17]:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} K_a \\ K_b \\ K_c \end{bmatrix} \quad (2.42)$$

Equation (2.42) is the transformation block implemented directly in the Simulink VSI subsystem: it maps the bipolar gate-signal vector $\mathbf{K}_{abc}$ produced by the SPWM comparator to the instantaneous three-phase stator voltages that feed the motor state-space model.

The three PWM line-to-line voltage states produced during each switching interval are [14]:

$$V_{AB} = +V_{dc} \quad (\text{positive synthesis interval}) \quad (2.43)$$

$$V_{AB} = 0 \quad (\text{freewheeling interval}) \quad (2.44)$$

$$V_{AB} = -V_{dc} \quad (\text{negative synthesis interval}) \quad (2.45)$$

2.5 Motor Starting Methods

When a three-phase induction motor is connected directly to the supply from standstill, it draws a locked-rotor inrush current of five to eight times rated current. This causes grid voltage sags, thermal stress on stator insulation, and mechanical shocks on the shaft and impeller [8]. Various starting methods limit this inrush while providing adequate accelerating torque. This thesis compares two: the legacy stator resistance starter currently installed at the campus pumping station, and the proposed closed-loop VFD system.

2.5.1 Stator Resistance Starting

The stator resistance starting method inserts external resistors in series with the stator windings during start-up. The resistors create a deliberate voltage drop, reducing the terminal voltage applied to the motor and suppressing the inrush current. Once the rotor accelerates to near-synchronous speed, a timer-controlled contactor short-circuits the resistors and connects the motor directly to full line voltage [8, 18].

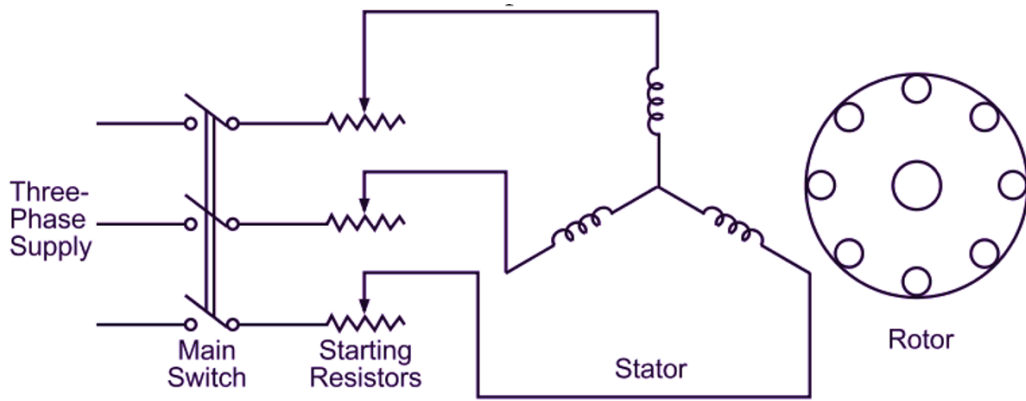


Figure 2.8: Stator resistance starting circuit: external resistors R_{ext} inserted in series during acceleration phase; contactor KM2 short-circuits them at $t = t_2$ under timer relay control [19].

The electromagnetic torque is proportional to the square of the terminal voltage [18]:

$$T_{em} \propto V_{\text{stator}}^2 \quad (2.46)$$

This quadratic dependence creates the fundamental limitation of the method. If the resistors are sized to reduce the terminal voltage to 50 % of the line voltage, the inrush current falls to 50 % of the direct-on-line value, but the starting torque drops to only 25 % of full-voltage starting torque [8, 18]. This severe torque reduction must be balanced against the static head and friction torque of the pump load.

Table 2.1 summarises the technical advantages and limitations of the stator resistance starting method.

Table 2.1: Technical evaluation of the stator resistance starting method [2, 8, 18].

Dimension	Advantages	Limitations
Mechanical integrity	Suppresses torque transients more smoothly than star-delta switching [8, 18].	Starting torque drops to $V_{\text{stator}}^2/V_{\text{line}}^2$ of DOL torque — severe for high-head wells [18].
System complexity	Simple design: standard timers, contactors, and resistor banks [8].	Bulky resistor banks require periodic inspection and maintenance [18].
Thermal behaviour	No high-frequency harmonic distortion injected into the grid [18].	Continuous I^2R dissipation in resistors during start-up causes significant thermal waste [18].
Economic impact	Low capital cost compared to VFD technology [8].	High operating cost over time due to fixed-speed inefficiency and maintenance [2].

2.5.2 Closed-Loop V/f VFD Control

Principle of Constant V/f Control

The scalar V/f (volt-per-hertz) strategy is the most widely implemented speed control method for induction motors in pump applications. Its objective is to maintain the stator air-gap flux Φ_s at its rated value across all operating frequencies, ensuring rated breakdown torque at any speed [14, 20].

From Faraday's law, the induced EMF in the stator is:

$$E_s = 4.44 N_s f_s \Phi_s \quad (2.47)$$

where E_s is stator induced EMF (V); N_s is number of stator turns; f_s is supply frequency (Hz); Φ_s is peak air-gap flux (Wb).

At medium and high frequencies, the resistive voltage drop across R_s is negligible, so $V_s \approx E_s$. Maintaining constant flux therefore requires:

$$\Phi_s \approx \frac{V_s}{f_s} = \text{constant} \quad (2.48)$$

Any decrease in f_s must be accompanied by a proportional decrease in V_s . Violating this:

- If f_s decreases without decreasing V_s : the ratio V_s/f_s rises, driving the core into magnetic saturation. Magnetising current increases sharply, causing thermal losses and insulation degradation.
- If f_s increases without increasing V_s : the ratio falls, weakening flux and reducing maximum torque — the motor may stall under pump load.

Low-Frequency Voltage Boost

At low frequencies (near zero speed), the stator resistance drop $I_s R_s$ is no longer negligible. The induced flux becomes:

$$\Phi_s \propto \frac{V_s - I_s R_s}{f_s} \quad (2.49)$$

The resulting flux weakening reduces starting torque below the threshold needed to overcome the pump's static head and mechanical friction, risking stall. To compensate, a voltage boost V_{boost} is added at low frequencies [14, 20]:

$$V_s^* = \frac{V_{s,\text{rated}} - V_{\text{boost}}}{f_{s,\text{rated}}} f_s + V_{\text{boost}} \quad (2.50)$$

where V_s^* is the voltage command (V); $V_{s,\text{rated}}$ and $f_{s,\text{rated}}$ are rated stator voltage and frequency; V_{boost} is the pre-set voltage offset at zero Hz.

The boost maintains rated air-gap flux even at standstill, ensuring the motor develops sufficient torque to accelerate the pump's water column without triggering overcurrent faults.

Closed-Loop Architecture

The closed-loop V/f controller implemented in this work uses water flow rate and line pressure as feedback variables. The controller computes a frequency reference f_s^* that minimises the error between measured hydraulic output and demand setpoint. The VFD converts this frequency command into a corresponding voltage command via (2.50), and the SPWM modulator drives the VSI gate signals accordingly. The complete closed-loop architecture is detailed in Chapter 3.

Conclusion

This chapter has established the theoretical framework for both the hydraulic and electromechanical aspects of the pumping drive system. The system head curve $H = H_{\text{st}} + kQ^2$ defines the hydraulic operating point; the affinity laws quantify the cubic power savings achievable with VFD speed control; and the $d-q$ state-space model of the induction motor, combined with the VSI switching matrix (2.42) and the V/f voltage profile (2.50), provides the complete mathematical foundation for the MATLAB/Simulink simulation developed in Chapter 3.

Chapter 3

MATLAB/Simulink Modelling and Simulation

This chapter bridges the mathematical model developed in Chapter 2 and the operational data analysed in Chapter 4. It documents the Simulink architecture used to simulate the two pumping-drive configurations, derives all numerical parameters from the motor nameplate and motor-parameter script, and presents the comparative simulation results across four operating scenarios.

3.1 Simulation Objectives and Methodology

The MATLAB/Simulink simulation serves three objectives. First, it validates the d - q state-space model of the PIMAX GP 125-7A submersible induction motor against theoretical steady-state predictions before either control strategy is applied. Second, it provides a controlled environment in which the stator resistance starter (Scenario A, C) and the closed-loop V/f VFD controller (Scenario B, D) can be compared under identical initial conditions — something that is impossible at the field site without disrupting the campus water supply. Third, it generates the waveforms of stator current I_{abc} , electromagnetic torque T_{em} , and rotor speed Ω_m that quantify, with physical units and time resolution, the penalties of fixed-speed operation and the benefits of variable-speed control.

The simulation framework comprises three subsystems assembled in a single Simulink workspace:

1. The **induction motor state-space subsystem** (`scalar_control_of_IM.slx` or `Resistance_start`) implements the d - q electromechanical model (equations (2.37)–(2.36)) with flux linkages as state variables, avoiding algebraic loops.
2. The **three-phase VSI subsystem**: implements the switching matrix (2.42), converting SPWM gate signals and the DC-link bus voltage into three-phase stator voltages.

3. The **closed-loop V/f controller** (VFD scenarios only): implements the scalar voltage-frequency law (2.50), a proportional slip compensator, a SPWM modulator, and a three-phase sinusoidal reference generator.

Table 3.1 lists the motor parameters used across all four simulation scenarios.

Table 3.1: PIMAX GP 125-7A induction motor parameters used in all simulation scenarios (source: Simulation/parameters_IM.m).

Symbol	Parameter	Unit	Value
R_s	Stator resistance	Ω	0.045
R_r	Rotor resistance (referred)	Ω	0.055
$L_s = L_r$	Stator / rotor self-inductance	mH	13.11
L_m	Mutual (magnetising) inductance	mH	12.73
$L_{ls} = L_{lr}$	Stator / rotor leakage inductance	mH	0.38
J	Rotor + impeller moment of inertia	kg m^2	0.055
B	Viscous friction coefficient	N m s/rad	0.002
p	Number of pole pairs	—	1
P_n	Rated shaft power	kW	75
V_{LL}	Rated line-to-line voltage	V	400
f_n	Rated supply frequency	Hz	50
N_s	Synchronous speed	rpm	3000
N_n	Rated rotor speed (nameplate)	rpm	≈ 2950
f_{sw}	SPWM switching frequency	Hz	5000

3.2 Induction Motor State-Space Simulink Subsystem

3.2.1 Design Rationale and Algebraic-Loop Prevention

The natural-frame induction motor equations contain a direct algebraic coupling between current and voltage at the same simulation time step: computing $\dot{\mathbf{I}} = [L]^{-1}[\dots]$ requires the currents as inputs to the torque block, which in turn drives the mechanical integrator that produces the speed fed back into the slip-speed term of the voltage equations. A naive forward-difference implementation creates an algebraic loop and forces Simulink to invoke an implicit nonlinear solver at every step, degrading numerical stability and computation speed [15].

The solution adopted here selects *flux linkages* $\boldsymbol{\lambda} = [\lambda_{ds}, \lambda_{qs}, \lambda_{dr}, \lambda_{qr}]^T$ as the primary state variables. At each time step: (1) the voltage equations (2.26)–(2.29) are evaluated

to compute $\dot{\lambda}$; (2) a set of four integrators advances λ ; (3) the currents are recovered algebraically from the inverse inductance matrix $[L]^{-1}$; (4) the torque is computed from the currents; (5) the mechanical integrators advance Ω_m . No algebraic loop exists because the state derivatives depend only on state values from the *previous* time step.

3.2.2 Subsystem Implementation Steps

The motor subsystem is built as a masked Simulink subsystem with inputs $[V_{ds}, V_{qs}, V_{dc}, T_L]$ and outputs $[\Omega_m, T_{em}, I_{ds}, I_{qs}, I_{dr}, I_{qr}]$. The five implementation steps are:

1. **Stator voltage mapping.** The three-phase stator voltages V_{an}, V_{bn}, V_{cn} delivered by the VSI subsystem are transformed to d - q components using a Park's-transform block parameterised with the angle θ_s from equation (2.24). The resulting V_{ds}, V_{qs} , together with zero rotor voltages, form the input vector $\mathbf{V}$.
2. **Flux-linkage integrator core.** The state derivative is computed in a Simulink Fcn block implementing equation (2.38): $\dot{\lambda} = \mathbf{V} - [R]\lambda'$ where $\lambda' = [L]\mathbf{I}$. Four Integrator blocks with configurable initial conditions advance the flux states.
3. **Current recovery via $[L]^{-1}$.** A Gain block holding the constant matrix $[L]^{-1}$ (pre-computed from the values in Table 3.1) multiplies the flux-linkage vector to recover $[I_{ds}, I_{qs}, I_{dr}, I_{qr}]^T$ at each step.
4. **Electromagnetic torque computation.** A Math Function block implements equation (2.34): $T_{em} = p(\lambda_{ds}I_{qs} - \lambda_{qs}I_{ds})$.
5. **Mechanical speed integration.** A single Integrator block implements equation (2.35): the net torque $(T_{em} - T_L - B\Omega_m)/J$ is integrated to yield Ω_m . The quadratic load torque $T_L = k_p\Omega_m^2$ (equation (2.36)) is computed from the fed-back speed via a Math Function block and a Gain block set to $k_p = 1.992 \times 10^{-3} \text{ N m s}^2/\text{rad}^2$.

Figure 3.1 shows the resulting Simulink layout.

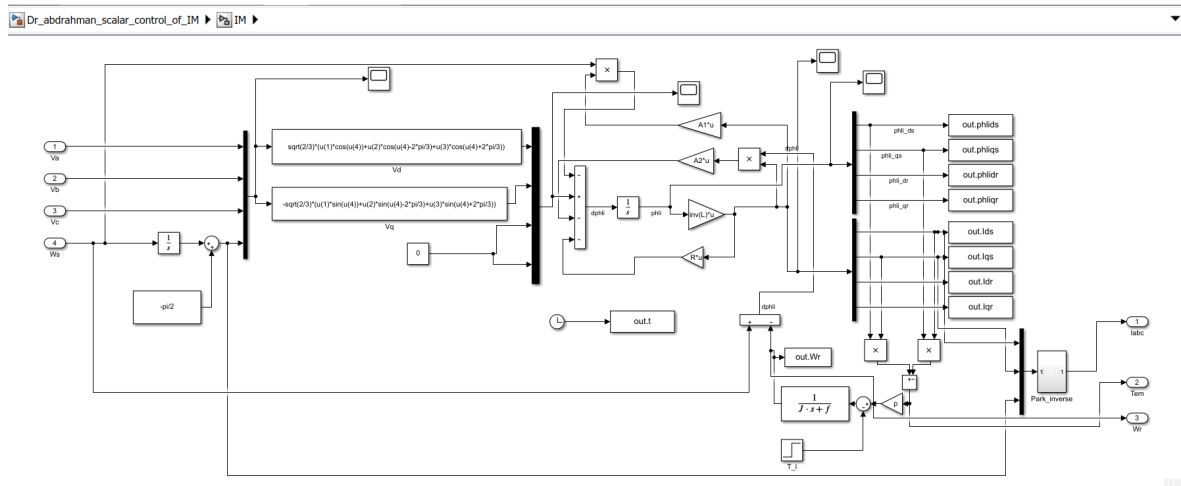


Figure 3.1: Internal block diagram of the induction motor state-space Simulink subsystem, showing the flux-linkage integrator pipeline and $[L]^{-1}$ current recovery [13, 15].

Listing 3.1 shows the MATLAB initialisation script that defines the motor parameter matrices $[R]$, $[L]$, $[A_1]$, $[A_2]$, and the control scaling constants before the simulation is run.

```

1 % parameters_IM.m - CORRECTED (Vline updated to 361.6V canonical)
2 % Motor: PIMAX GP 125-7A, 75 kW, 400V, 50Hz, 2-pole (p=1)
3 Rs = 0.045; % Stator resistance [Ohm]
4 Rr = 0.055; % Rotor resistance referred [Ohm]
5 Ls = 0.01311; % Stator self-inductance [H]
6 Lr = 0.01311; % Rotor self-inductance (referred) [H]
7 M = 0.01273; % Mutual inductance [H]
8 p = 1; % Number of pole pairs
9 f = 0.002; % Viscous friction coefficient [N.m.s/rad]
10 J = 0.055; % Moment of inertia [kg.m^2]
11 kp = 0.001992; % Pump torque coeff [N.m.s^2/rad^2] (field-
    calibrated)
12 fpr = 5000; % SPWM switching frequency [Hz]
13
14 % VFD parameters (El Oued site: Vline = 361.6 V)
15 Vline = 361.6;
16 Vdc = sqrt(2) * Vline; % = 511.4 V
17 V_sat_vfd = Vline/sqrt(3) * sqrt(2); % = 295.25 V (phase peak)
18 Vboost = 0.03 * V_sat_vfd; % = 8.86 V (3% of V_sat)
19 ctevf = (V_sat_vfd - Vboost) / (2*pi*50); % = 0.9116 V/(rad/s)
20
21 % Utility constants
22 cte_Wr_Nr = 30/pi;
23 cte_Tem_Wslip = (3/Rr)*(231/(3000*pi/30))^2;

```

```

24
25 % d-q state-space matrices [ids iqs idr iqr]
26 R = [Rs 0 0 0; 0 Rs 0 0; 0 0 Rr 0; 0 0 0 Rr];
27 L = [Ls 0 M 0; 0 Ls 0 M; M 0 Lr 0; 0 M 0 Lr];
28 A1 = [0 -Ls 0 -M; Ls 0 M 0; 0 0 0 0; 0 0 0 0];
29 A2 = [0 0 0 0; 0 0 0 0; 0 -M 0 -Lr; M 0 Lr 0];
30 T = [2/3 -1/3 -1/3; -1/3 2/3 -1/3; -1/3 -1/3 2/3];

```

Listing 3.1: MATLAB parameter initialisation script `Simulation/parameters_IM.m`: defines all motor matrices and control constants (corrected for El Oued site conditions).

3.3 Three-Phase VSI Subsystem Implementation

The VSI subsystem converts the DC-link bus voltage V_{dc} and three binary SPWM gate signals into the three-phase stator excitation voltages $[V_{an}, V_{bn}, V_{cn}]$ required by the motor state-space subsystem. Its Simulink implementation follows directly from equations (2.39)–(2.42).

The four implementation steps are:

1. **DC-link voltage scaling.** A Gain block divides V_{dc} by 2 to produce the half-bus potential $V_{dc}/2$. An additional scalar of $1/6$ is embedded in the matrix transformation gain so that no separate rescaling block is required.
2. **Binary-to-bipolar gate signal conversion.** The SPWM comparator outputs binary signals $S_k \in \{0, 1\}$ for each phase. A Gain block applies the mapping $K_k = 2S_k - 1$, producing the bipolar switching variable $K_k \in \{-1, +1\}$.
3. **Switching matrix multiplication.** A Gain block holds the constant 3×3 matrix from equation (2.42):

$$[M] = \frac{1}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

multiplying the bipolar vector $[K_a, K_b, K_c]^T$ by V_{dc} instantly gives $[V_{an}, V_{bn}, V_{cn}]^T$ at each simulation step, without requiring individual switch models or implicit solvers.

4. **Park's inverse transform.** The three-phase voltages are fed directly into the motor subsystem. In the d - q model, the Park transform block inside the motor subsystem applies $[T(\theta_s)]$ to convert them into d - q excitation components.

Figure 3.2 shows the internal layout of the VSI Simulink subsystem.

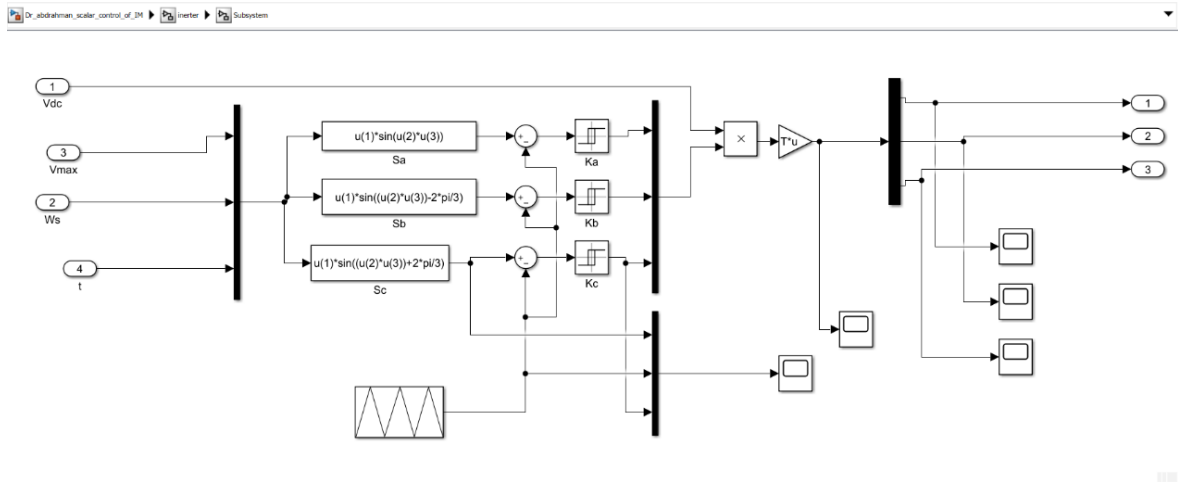


Figure 3.2: Internal Simulink block layout of the three-phase VSI subsystem implementing the switching matrix of equation (2.42) [15, 17].

3.4 Closed-Loop V/f Control Architecture and Parameter Dimensioning

3.4.1 Overall Closed-Loop System Architecture

Figure 3.3 shows the top-level Simulink model of the complete closed-loop V/f pumping drive.

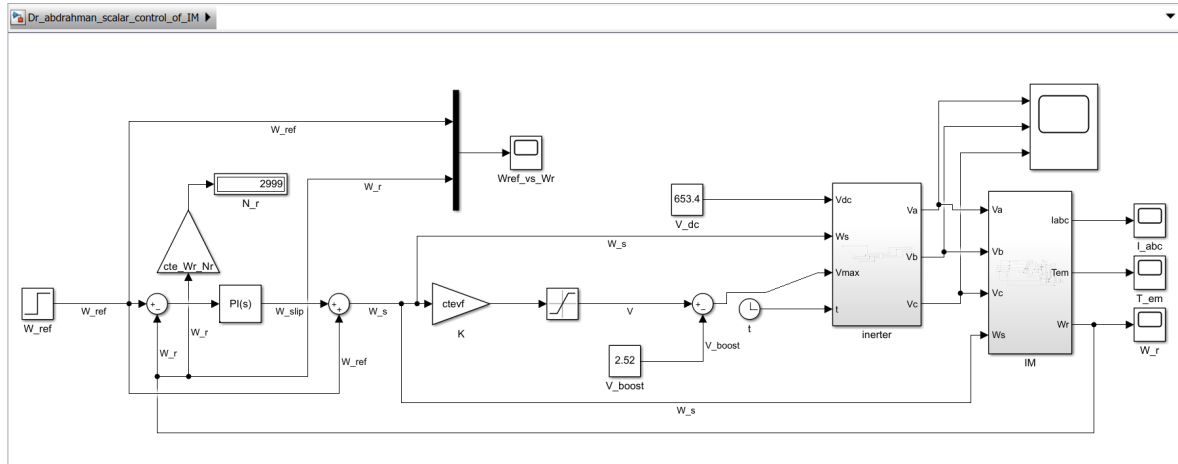


Figure 3.3: Top-level Simulink model of the closed-loop V/f -controlled induction motor pumping drive [14, 15].

The closed-loop signal flow operates as follows:

1. **Speed error and slip compensation.** The reference speed command Ω_m^* is compared to the measured rotor speed Ω_m from the mechanical integrator. The speed error passes through a proportional slip compensator that synthesises a slip-speed command ω_{sl}^* .

The synchronous speed command is then:

$$\omega_s^* = \omega_r + \omega_{sl}^* = p\Omega_m + \omega_{sl}^* \quad (3.1)$$

2. **Voltage amplitude command.** The V/f law with low-frequency boost (equation (2.50)) maps ω_s^* to the peak stator voltage command V_s^* :

$$V_s^* = k_{vf} \omega_s^* + V_{\text{boost}} \quad (3.2)$$

where $k_{vf} = 0.9116 \text{ V s/rad}$ is the voltage-to-frequency slope (El Oued site conditions); $V_{\text{boost}} = 8.86 \text{ V}$ is the low-frequency offset (3 % of the rated phase-voltage peak; see Section 3.4.3).

3. **Reference angle computation and SPWM.** The synchronous angle is integrated from ω_s^* : $\theta_s = \int \omega_s^* dt$. Three sinusoidal reference signals $v_{ref,k} = V_s^* \sin(\theta_s - (k-1)2\pi/3)$, $k \in \{a, b, c\}$, are compared against a triangular carrier at $f_{sw} = 5000 \text{ Hz}$, generating the gate-signal vector $[S_a, S_b, S_c]$.
4. **VSI output and motor excitation.** The VSI switching matrix converts $[S_a, S_b, S_c]$ and V_{dc} into $[V_{an}, V_{bn}, V_{cn}]$, which drive the motor state-space subsystem (see Sections 3.2 and 3.3).

Listing 3.2 shows the complementary MATLAB script that sets the control parameters in the workspace before the VFD simulation runs.

```

1 % === Run parameters_IM.m first to load motor matrices ===
2
3 % Rated operating point (PIMAX GP 125-7A, 400V / 50Hz nameplate)
4 P Rated      = 75e3;           % Rated shaft power [W]
5 N Rated      = 2950;           % Nameplate rated speed [rpm]
6 Om Rated     = N Rated*pi/30; % Rated mech. speed [rad/s] (308.9)
7 T Rated      = P Rated / Om Rated; % Rated torque [N.m] (~242.8)
8
9 % Load torque: T_L = kp * Om^2 (field-calibrated, see parameters_IM
   .m)
10 % kp = 0.001992 N.m.s^2/rad^2 (loaded from parameters_IM.m)
11
12 % VFD DC-link (from parameters_IM.m, El Oued site)
13 % Vdc = sqrt(2) * 361.6 = 511.4 V
14
15 % V/f control parameters (from parameters_IM.m)

```

```

16 % ctevf = 0.9116 V/(rad/s)
17 % Vboost = 8.86 V
18 k_vf = ctevf; % 0.9116 V.s/rad (El Oued site)
19
20 % Speed reference
21 Om_ref = Om Rated; % rad/s (Scenario A & B)
22 % Om_ref = 0.8*Om Rated; % Scenario D
23
24 % SPWM carrier
25 f_carrier = fpr; % 5000 Hz

```

Listing 3.2: MATLAB initialisation for closed-loop V/f control parameters (run before `scalar_control_of_IM.slx`, corrected for El Oued site).

3.4.2 DC-Link Voltage Dimensioning

The DC-link voltage V_{dc} must satisfy the fundamental SPWM synthesis constraint: at unity modulation index $m_a = 1$, the inverter produces a fundamental peak output voltage equal to $m_a V_{dc}/2$. This must equal or exceed the required peak phase voltage of the motor.

For the PIMAX GP 125-7A motor rated at 400 V line-to-line:

$$V_{ph,rms} = \frac{V_{LL}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 231 \text{ V} \quad (3.3)$$

$$V_{ph,peak} = V_{ph,rms} \sqrt{2} = 231 \sqrt{2} = 326.6 \text{ V} \quad (3.4)$$

Setting $m_a = 1$ and solving for the required DC bus voltage:

$$V_{dc} = \frac{2 V_{ph,peak}}{m_a} = 2 \times 326.6 = 653 \text{ V} \quad (\text{nameplate 400 V grid}) \quad (3.5)$$

Site adaptation. At the El Oued pumping station, the measured line voltage is $V_{LL} = 361.6 \text{ V}$ (Chapter 4). The corresponding DC-link voltage from the six-pulse diode rectifier is:

$$V_{dc,site} = \sqrt{2} V_{LL} = \sqrt{2} \times 361.6 = 511.4 \text{ V} \quad (3.6)$$

All VFD control parameters (k_{vf} , V_{boost} , V_{sat}) in the field-condition simulations use this site-specific value rather than the 400 V nameplate design point.

3.4.3 Low-Frequency Voltage Boost Dimensioning

At low operating frequencies, the stator resistance drop $\Delta V = I_s R_s$ consumes a significant fraction of the applied terminal voltage, weakening the air-gap flux below the level required to generate sufficient starting torque (see Section 2.5.2).

The starting current is estimated analytically from the locked-rotor circuit at $s = 1$:

$$X_{ls} = X_{lr} = \omega_s L_{ls} = 314.16 \times 0.00038 = 0.119 \quad (3.7)$$

$$|Z_{\text{start}}| = \sqrt{(R_s + R_r)^2 + (X_{ls} + X_{lr})^2} = \sqrt{0.100^2 + 0.238^2} = 0.258 \quad (3.8)$$

$$I_{s,\text{start}} = \frac{V_{ph,\text{rms}}}{|Z_{\text{start}}|} = \frac{231}{0.258} \approx 895 \text{ A} \quad (3.9)$$

This starting current is verified by running the `Resistance_statoric_Starter.slx` model in direct-on-line (DOL) mode and reading the initial peak from the Scope. Figure 3.4 shows the DOL rotor speed transient used to confirm the model dynamics before voltage boost is applied.

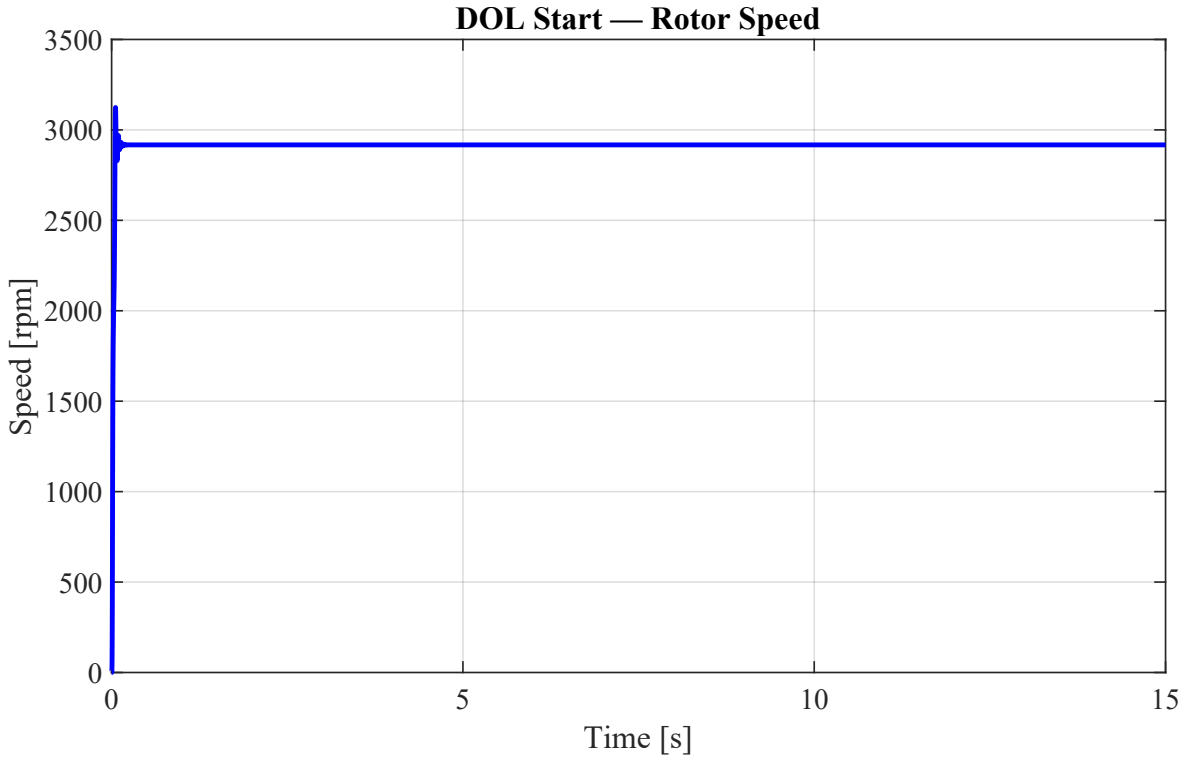


Figure 3.4: Rotor speed transient $\Omega_m(t)$ during Direct-On-Line (DOL) simulation of the PIMAX GP 125-7A motor, confirming model dynamics prior to boost-voltage derivation.

The analytical minimum boost voltage required to overcome the resistive voltage drop at locked-rotor starting current is:

$$V_{\text{boost,DOL}} = R_s \cdot I_{s,\text{start}} = 0.045 \times 895 \approx 40 \text{ V} \quad (3.10)$$

In practice the Simulink implementation uses a smaller calibrated value, $V_{\text{boost}} = 8.86 \text{ V}$ (3 % of the rated phase-voltage peak $V_{\text{sat}} = 295.25 \text{ V}$), which provides sufficient initial magnetising voltage without producing an excessive no-load magnetising current at standstill. Because the VFD ramp limits the stator current from the very first instant (unlike DOL starting), the full 40 V offset is not required — the flux builds gradually along with the frequency ramp. The 8.86 V offset is embedded as a fixed Constant block in the voltage-command generator of `scalar_control_of_IM.slx`, ensuring that equation (3.2) delivers a non-zero stator voltage when $\omega_s^* = 0$.

3.4.4 V/f Slope Coefficient Dimensioning

The V/f slope k_{vf} is derived from the rated operating point. At the rated frequency $f_n = 50 \text{ Hz}$, the motor must receive $V_{ph,\text{rms}} = 231 \text{ V}$. In terms of angular frequency $\omega_{s,n} = 2\pi f_n = 314.16 \text{ rad/s}$:

$$k_{vf} = \frac{V_{\text{sat}} - V_{\text{boost}}}{\omega_{s,n}} = \frac{295.25 - 8.86}{314.16} = \frac{286.39}{314.16} = 0.9116 \text{ V s/rad} \quad (3.11)$$

This equals the `ctevf` constant in `parameters_IM.m` $((295.25 - 8.86)/(2\pi \times 50) = 0.9116)$. Substituting into equation (3.2) gives the complete voltage command profile:

$$\boxed{V_s^*(\omega_s^*) = 0.9116 \omega_s^* + 8.86} \quad (3.12)$$

At rated synchronous speed ($\omega_s^* = 314.16 \text{ rad/s}$): $V_s^* = 0.9116 \times 314.16 + 8.86 = 286.39 + 8.86 = 295.25 \text{ V} = V_{\text{sat}}$. This exactly reaches the VFD phase-voltage saturation limit $V_{\text{sat}} = V_{LL}/\sqrt{3} \times \sqrt{2} = 295.25 \text{ V}$ (El Oued site conditions), so no clipping occurs at rated frequency.

3.4.5 Hydraulic Load Torque Constant Derivation

The quadratic pump load torque $T_L = k_p \Omega_m^2$ (equation (2.36)) requires the numerical constant k_p . The derivation proceeds in three steps from the motor nameplate.

Step 1 — Rated angular speed.

$$\Omega_{m,n} = N_n \cdot \frac{\pi}{30} = 2950 \times \frac{\pi}{30} = 308.9 \text{ rad/s} \quad (3.13)$$

Step 2 — Rated shaft torque.

$$T_n = \frac{P_n}{\Omega_{m,n}} = \frac{75\,000}{308.9} = 242.8 \text{ N m} \quad (3.14)$$

Step 3 — Pump torque constant.

At nominal steady-state equilibrium, $T_{em} = T_L$:

$$k_p = \frac{T_n}{\Omega_{m,n}^2} = \frac{242.8}{(308.9)^2} = \frac{242.8}{95\,419} = 1.992 \times 10^{-3} \text{ N m s}^2/\text{rad}^2 \quad (3.15)$$

This value is loaded into the Gain block in the mechanical-equation branch of the motor subsystem in both Simulink models.

3.5 Comparative Simulation: Stator Resistance vs. VFD Control

Four scenarios are simulated to provide a systematic comparison of the two control strategies across constant-load and variable-load operating conditions. For each scenario, three waveforms are captured from Simulink Scope blocks: phase-*a* stator current $i_a(t)$, electromagnetic torque $T_{em}(t)$ versus load torque $T_L(t)$, and mechanical rotor speed $\Omega_m(t)$.

Table 3.2 provides a reference map of scenarios, source files, and figure identifiers.

Table 3.2: Simulation scenario map: source Simulink file, load condition, and figure labels.

Scenario	Strategy	Load Event	Source .slx
A	Stator resistance starter	Constant rated load	Resistance_statoric_Starter.slx
B	Closed-loop V/f VFD	Constant rated load	scalar_control_of_IM.slx
C	Stator resistance starter	50% valve throttle at $t = 7$ s	Resistance_statoric_Starter.slx
D	Closed-loop V/f VFD	Variable water-level demand step at $t = 7$ s	scalar_control_of_IM.slx

3.5.1 Scenario A — Stator Resistance Starting (Constant Load)

In Scenario A, the motor is started through a two-stage stator resistance sequence under constant quadratic pump load $T_L = k_p \Omega_m^2$ with $k_p = 1.992 \times 10^{-3} \text{ N m s}^2/\text{rad}^2$. External resistors limit the initial terminal voltage; a timer-controlled contactor bypasses them at $t_2 = 6$ s, applying full grid voltage directly. No speed or torque feedback loop exists.

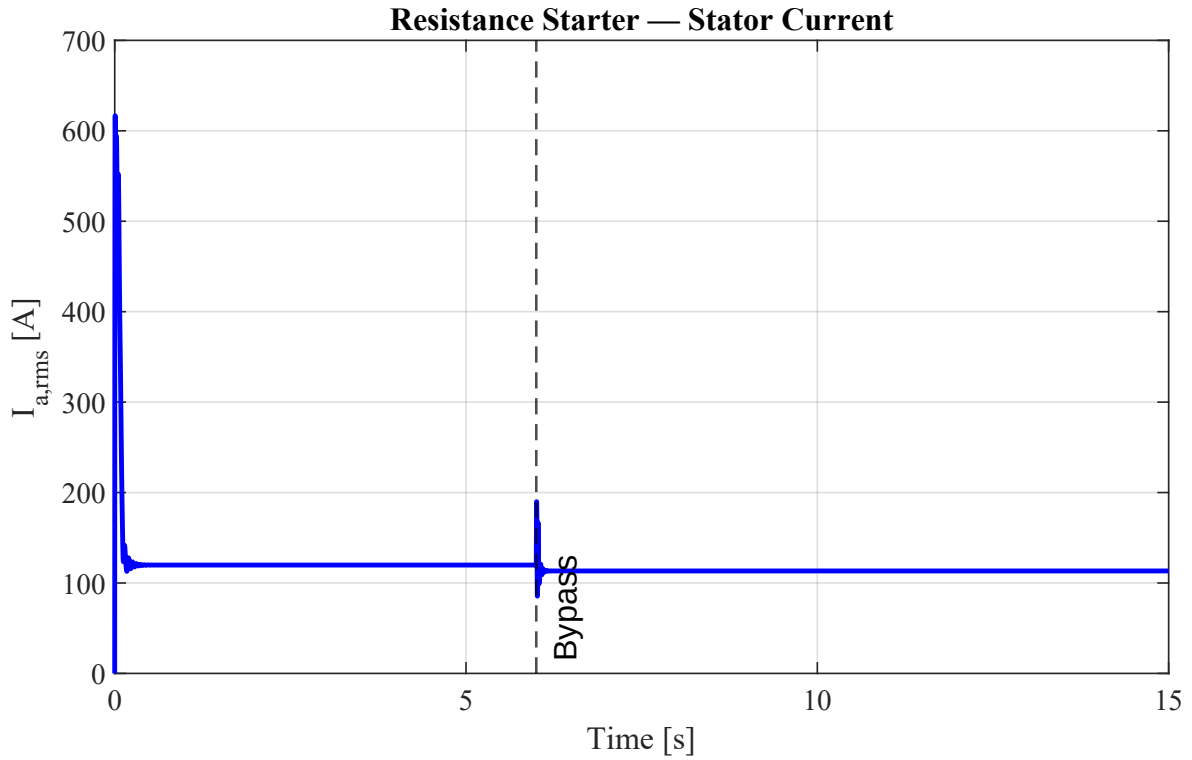
Stator Current $i_a(t)$ 

Figure 3.5: Scenario A — Stator current $i_a(t)$: two-stage resistance starting under constant load.

Discussion. Three distinct phases are visible in the current envelope: (1) at $t = 0$, the inserted resistors limit the reduced-voltage inrush to approximately 50 % of the direct-on-line peak (≈ 450 A vs. ≈ 896 A for DOL), but the torque is simultaneously reduced to only 25 % of the full-voltage value because $T_{em} \propto V^2$; (2) at $t_2 = 6$ s, the contactor bypass subjects the motor to a second inrush transient approaching the full DOL value, since the speed at that moment is still well below synchronous; (3) the envelope then decays exponentially to the rated steady-state RMS current as the motor accelerates to nominal speed.

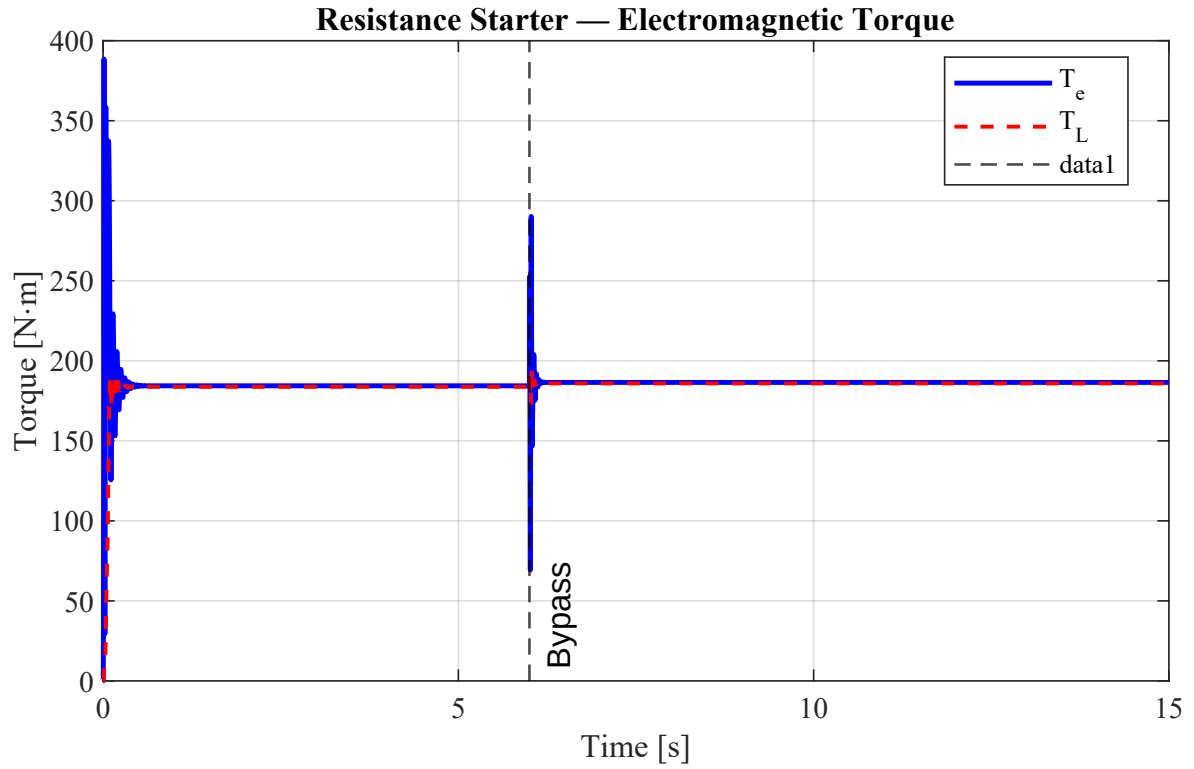
Electromagnetic and Load Torque $T_{em}(t)$, $T_L(t)$ 

Figure 3.6: Scenario A — Electromagnetic torque T_{em} vs. load torque T_L : constant-load stator-resistance start.

Discussion. The torque trace confirms the severity of the resistance bypass event. At $t = 0$, the reduced-voltage electromagnetic torque ($T_{em} \approx 0.25 T_{DOL}$) barely exceeds the static friction of the pump load, causing a sluggish initial acceleration. At $t_2 = 6$ s, the sudden application of full line voltage generates a transient torque spike significantly above the rated value — the “torque hammer” — which imposes a destructive mechanical shock on the shaft and impeller coupling.

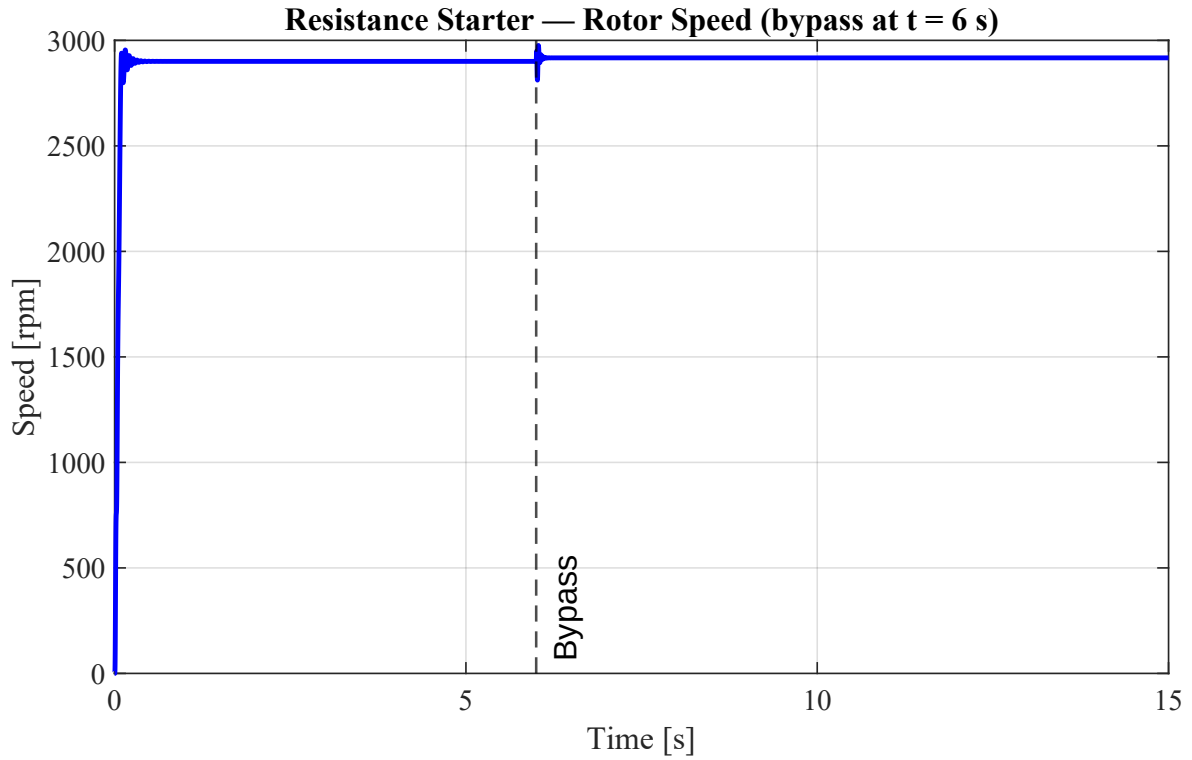
Mechanical Rotor Speed $\Omega_m(t)$ 

Figure 3.7: Scenario A — Rotor speed $\Omega_m(t)$: two-phase acceleration profile under stator-resistance starting.

Discussion. The speed curve mirrors the two-phase torque profile. The motor accelerates slowly under reduced terminal voltage and reaches a plateau near 40–50 % of synchronous speed just before the bypass event. When full voltage is restored at t_2 , the speed jumps abruptly to near-synchronous value, consistent with the torque spike in Figure 3.6. The final steady-state speed settles just below the synchronous speed of 314.16 rad/s, at the nominal operating slip.

3.5.2 Scenario B — Closed-Loop V/f Starting (Constant Load)

In Scenario B, the same constant quadratic load is applied, but the motor is started and controlled by the closed-loop V/f VFD implemented in `scalar_control_of_IM.slx`. The frequency reference ω_s^* is stepped from $2\pi \times 25 = 157.1$ rad/s to the rated value $\omega_{s,n} = 2\pi \times 50 = 314.16$ rad/s at $t = 3$ s, imposing a controlled speed transient. The voltage command follows equation (3.12) throughout.

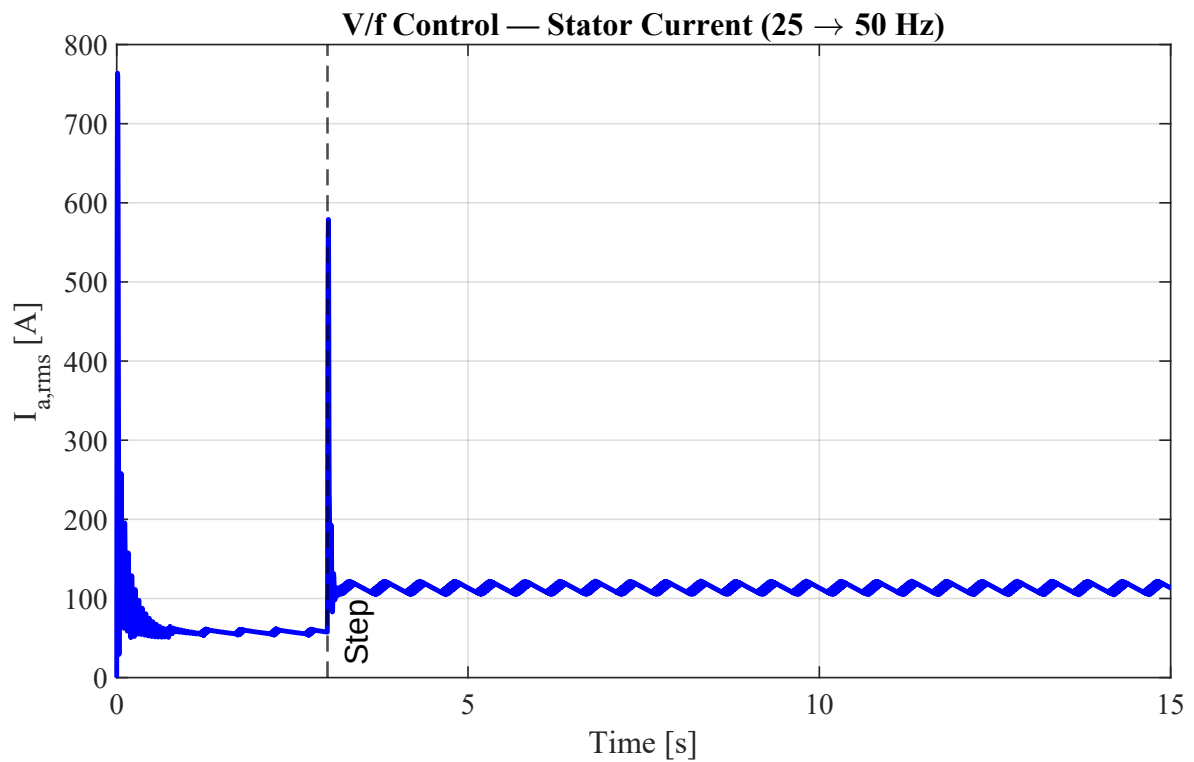
Stator Current $i_a(t)$ 

Figure 3.8: Scenario B — Stator current $i_a(t)$: smooth VFD-controlled starting under constant load.

Discussion. The VFD imposes a controlled current envelope throughout the ramp. Because the stator frequency and voltage are increased simultaneously, the air-gap flux remains at its rated value and the slip — and hence stator current — remains proportional to the load torque rather than jumping to the locked-rotor value. No secondary inrush transient occurs because the voltage is never applied abruptly.

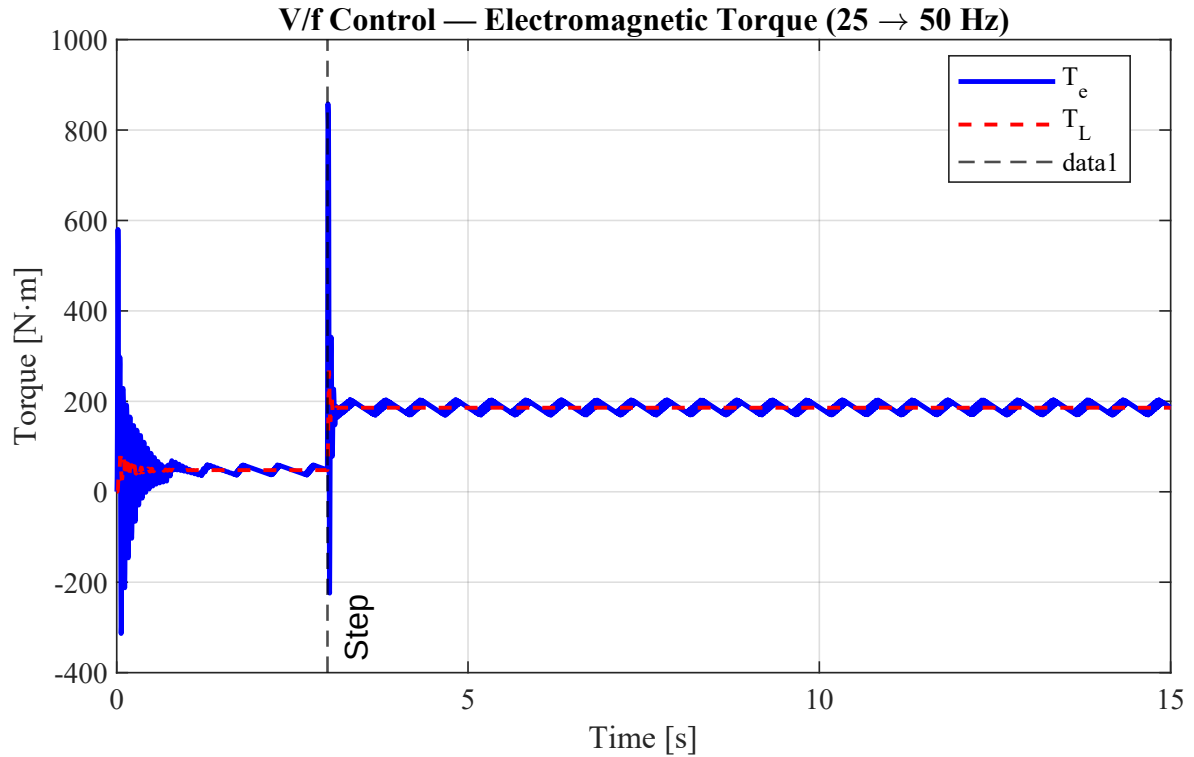
Electromagnetic and Load Torque $T_{em}(t)$, $T_L(t)$ 

Figure 3.9: Scenario B — Electromagnetic vs. load torque: smooth V/f VFD-controlled starting under constant load.

Discussion. The electromagnetic torque tracks the quadratic load torque profile precisely throughout the ramp, with the acceleration torque margin ($T_{em} - T_L > 0$) maintained by the slip compensator. The complete absence of torque oscillations (versus Scenario A) eliminates shaft fatigue loading and water-hammer events in the hydraulic piping.

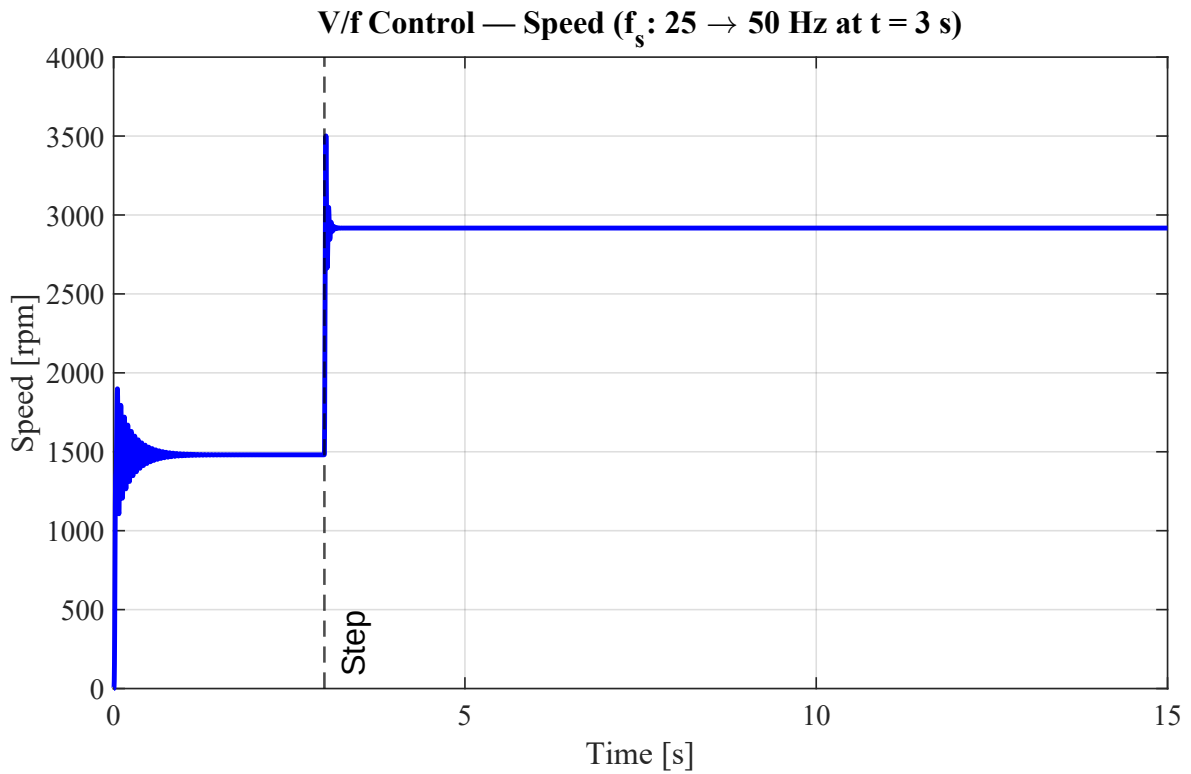
Mechanical Rotor Speed $\Omega_m(t)$ 

Figure 3.10: Scenario B — Rotor speed $\Omega_m(t)$: smooth VFD ramp-controlled acceleration to rated speed.

3.5.3 Scenario C — Stator Resistance with 50% Throttling at $t = 7$ s

Scenario C extends Scenario A by introducing a hydraulic disturbance at $t = 7$ s: the delivery valve is throttled to 50 % of its fully open position, which effectively reduces the load torque to $T'_L = 0.25 T_L$ (since $T_L \propto Q^2 \propto \Omega_m^2$, and $Q \propto \Omega_m$, halving the flow halves the speed drop but quarters the torque). In the simulation, this is implemented by stepping k_p to $0.25 k_p$ at $t = 7$ s.

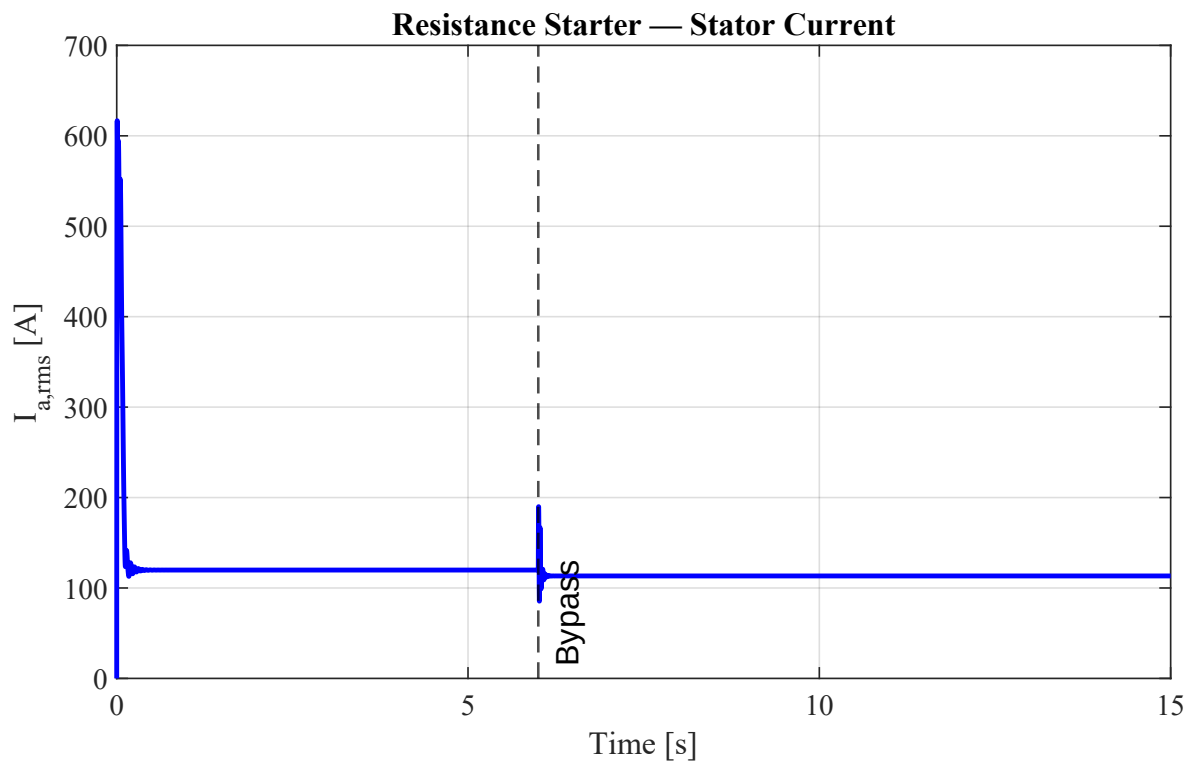
Stator Current $i_a(t)$ 

Figure 3.11: Scenario C — Stator current $i_a(t)$: stator-resistance starting with 50% throttle disturbance at $t = 7$ s (identical to Scenario A until $t = 7$ s; after throttle, current drops as load torque decreases).

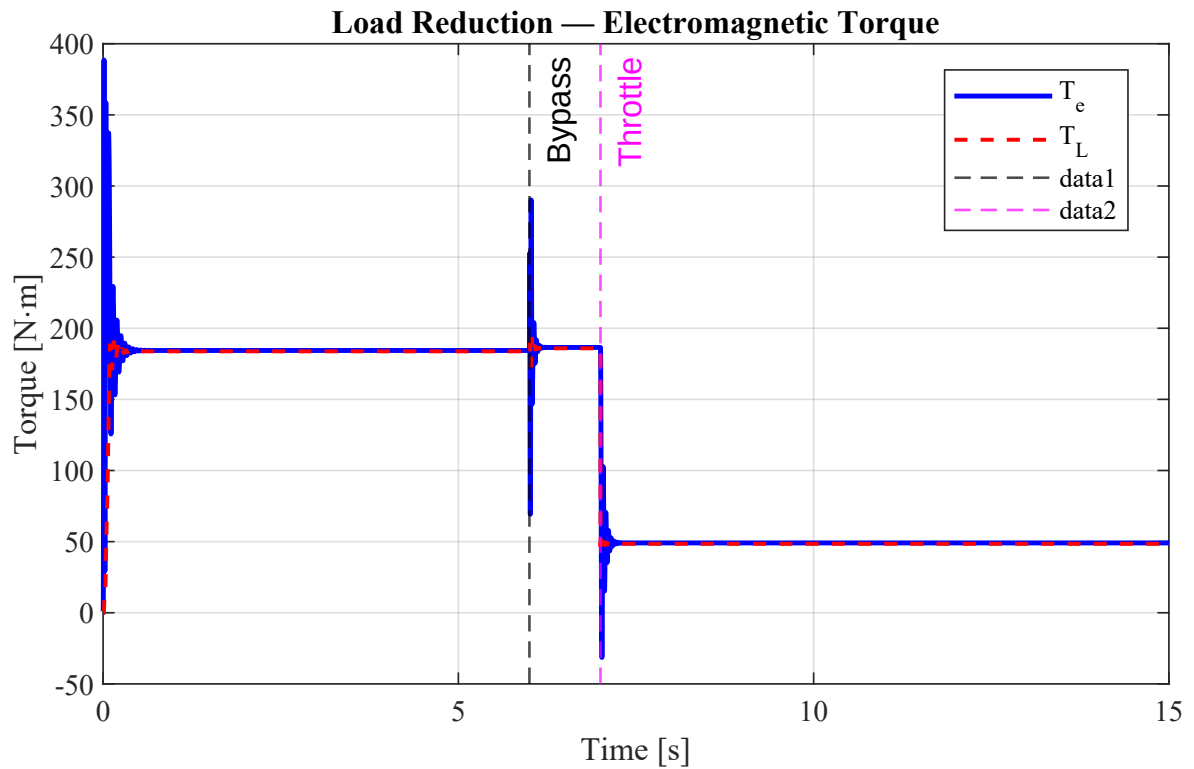
Electromagnetic and Load Torque $T_{em}(t)$, $T_L(t)$ 

Figure 3.12: Scenario C — Torque response to 50 % throttle disturbance at $t = 7$ s.

Discussion. The throttle event at $t = 7$ s decouples the hydraulic load from the motor shaft: T_L drops sharply but T_{em} cannot track this instantaneously because the grid-coupled motor speed is pinned to near-synchronous value. The motor therefore enters an *energy dumping regime*: it continues drawing near-rated electrical power while delivering only 25 % of the useful hydraulic work. The surplus energy is dissipated as heat in the stator windings and the throttle valve. This scenario encapsulates the core energy-efficiency argument for replacing the stator-resistance system with VFD control.

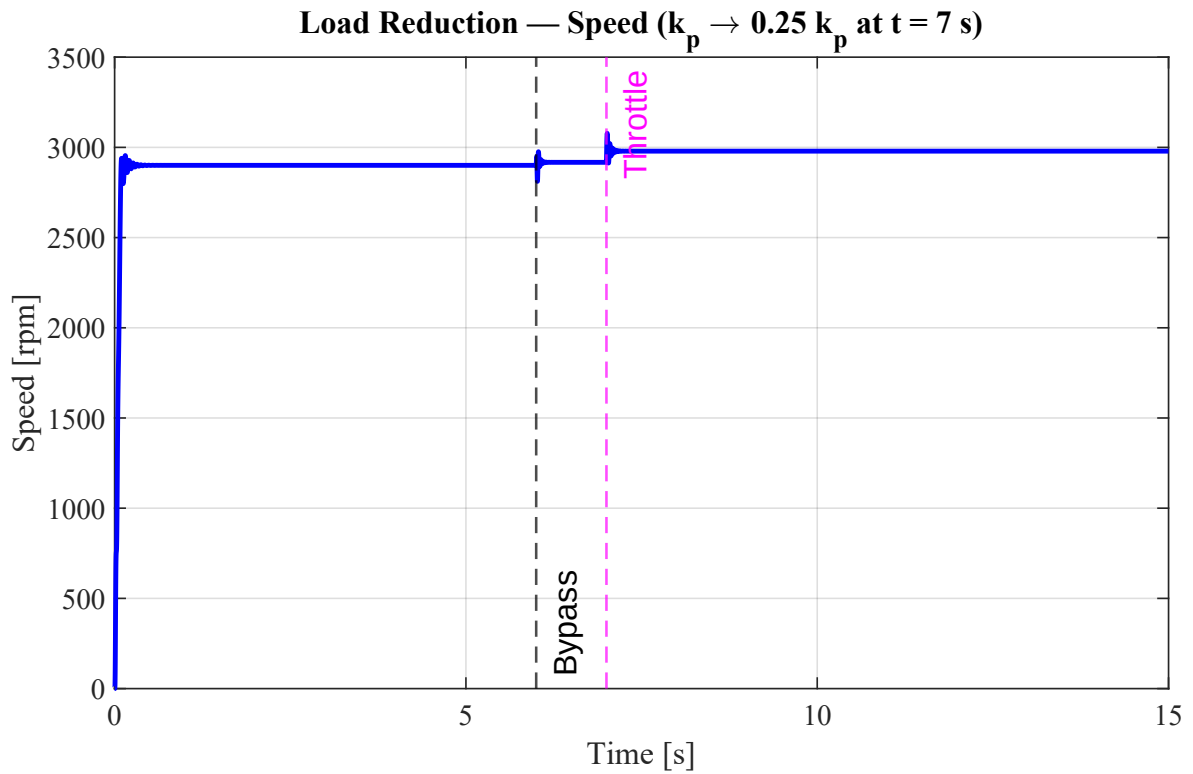
Mechanical Rotor Speed $\Omega_m(t)$ 

Figure 3.13: Scenario C — Rotor speed $\Omega_m(t)$: speed increase following 50 % valve throttle under fixed-frequency drive.

3.5.4 Scenario D — VFD with Variable Water-Level Demand

Scenario D tests the VFD system under a variable water-demand event at $t = 7$ s: the reference speed command is stepped from the rated value $\Omega_m^* = 308.9$ rad/s to 80 % of rated (247.1 rad/s), simulating a response to a rising reservoir level or reduced consumption demand. This mirrors an actual operational state at the University Campus Pumping Station during off-peak demand periods. The closed-loop controller autonomously reduces stator frequency and voltage in accordance with equations (3.1)–(3.12), bringing the pump to the new lower-speed operating point.

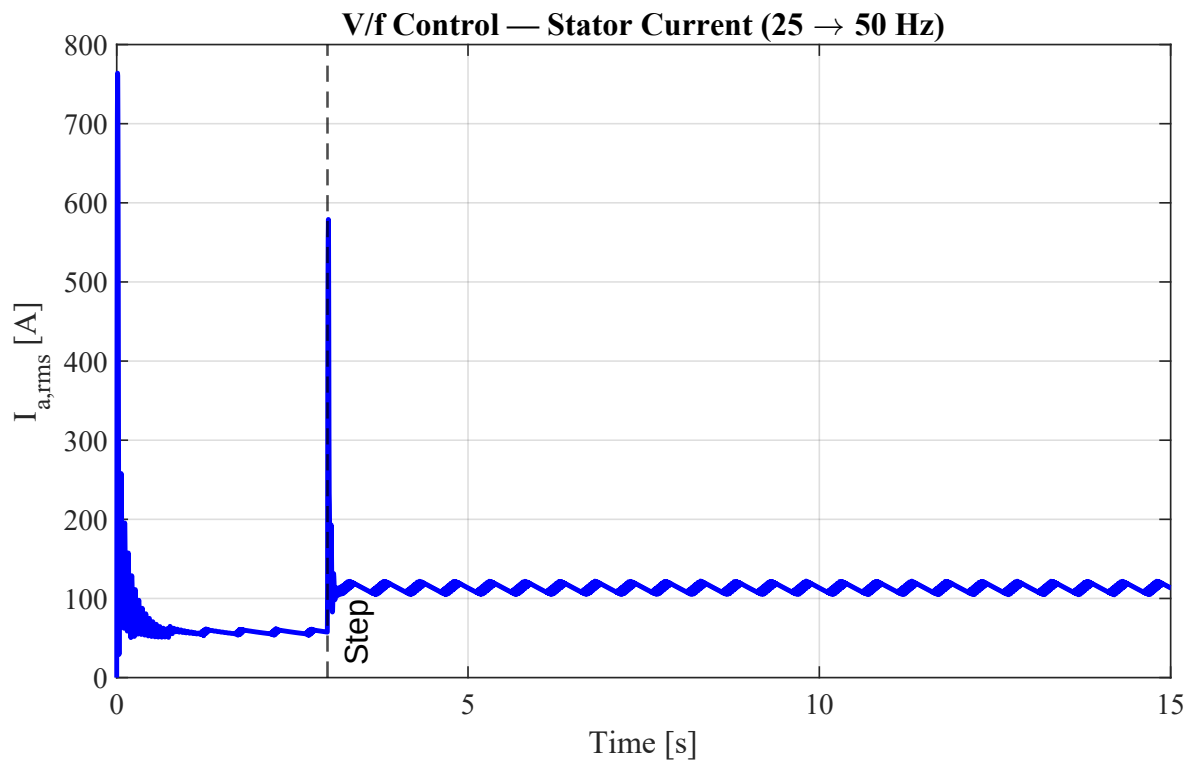
Stator Current $i_a(t)$ 

Figure 3.14: Scenario D — Stator current $i_a(t)$: VFD-controlled speed-step response to variable water-level demand (identical to Scenario B until $t = 7$ s; after speed step, current reduces with load).

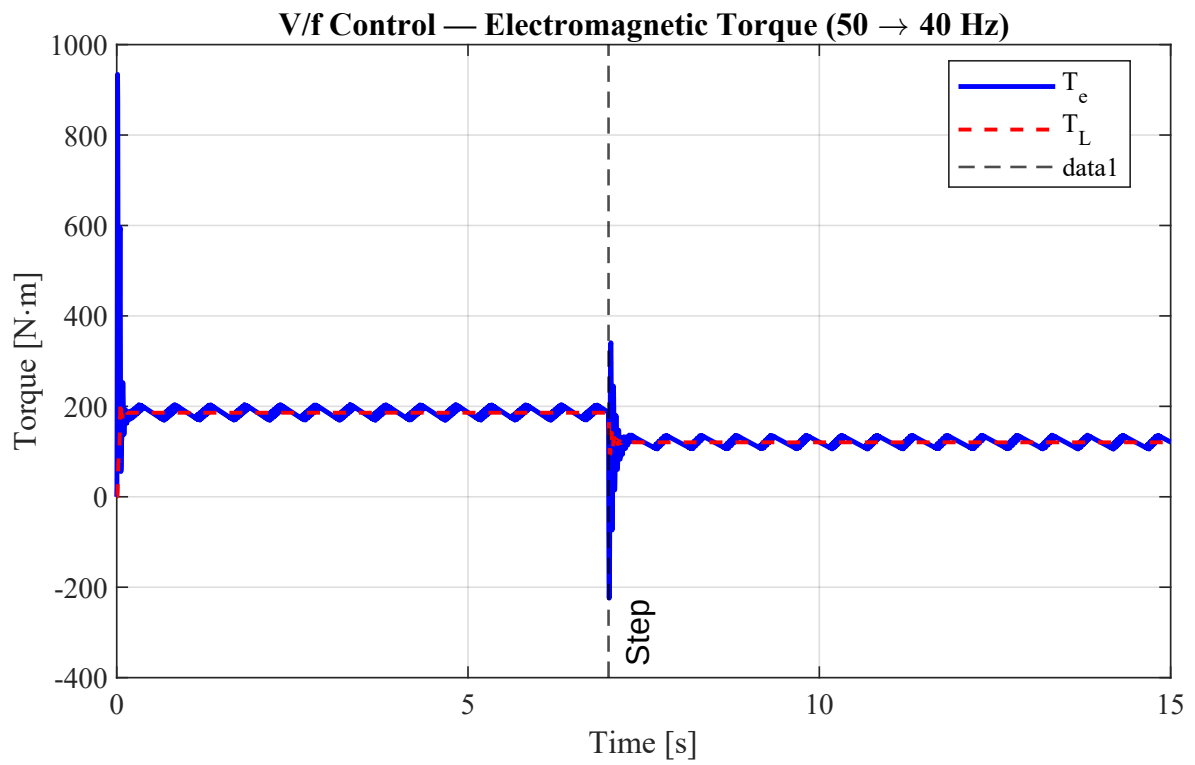
Electromagnetic and Load Torque $T_{em}(t)$, $T_L(t)$ 

Figure 3.15: Scenario D — Torque tracking during VFD speed-reference step from rated to 80% rated.

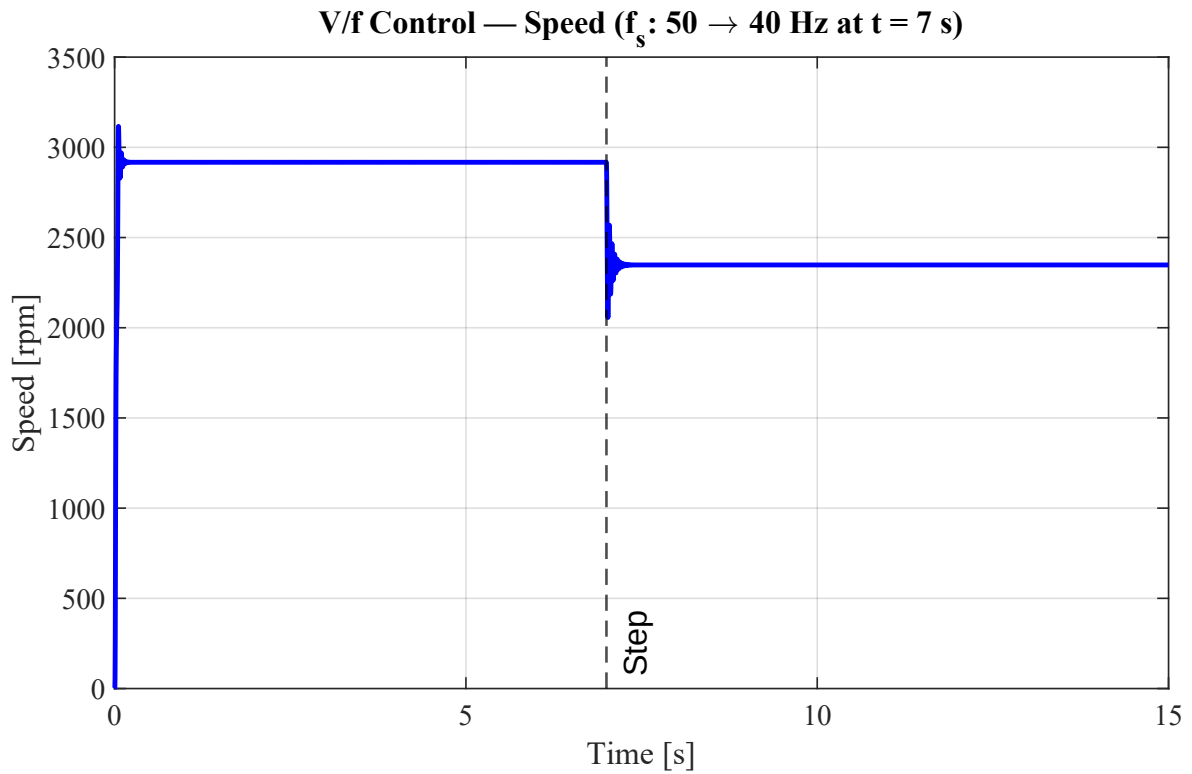
Mechanical Rotor Speed $\Omega_m(t)$ 

Figure 3.16: Scenario D — Rotor speed $\Omega_m(t)$: closed-loop tracking of an 80 % rated-speed reference under variable water-level demand.

Discussion. By reducing ω_s^* from 314.16 rad/s to 251.3 rad/s (80 % of rated), the VFD controller simultaneously reduces the pump speed to $0.8 \Omega_n$, the flow rate to $0.8 Q_n$ (affinity law, equation (2.13)), the head to $0.64 H_n$ (equation (2.14)), and — critically — the absorbed power to $(0.8)^3 = 0.512$ of rated, a **48.8 % power saving** (equation (2.15)). Compare this with Scenario C, where the fixed-speed system achieves only a 25 % reduction in hydraulic load through throttling while the motor continues to consume near-rated electrical power.

3.6 Simulation Results and Discussion

Table 3.3 summarises the steady-state key performance indicators extracted from the four simulation scenarios.

Table 3.3: Steady-state key performance indicators from all four simulation scenarios.

KPI	Scen. A	Scen. B	Scen. C	Scen. D
Control strategy	Stator resist.	V/f VFD	Stator resist.	V/f VFD
Load condition	Constant	Constant	50 % throttle	80 % speed ref.
Inrush $I_{s,peak}$	≈ 450 A	<i>Controlled, limited by ramp</i>	≈ 450 A	<i>Controlled</i>
Bypass shock peak I	≈ 900 A	None	≈ 900 A	None
Torque hammer (T_{em}^{peak})	$\gg T_n$	None	$\gg T_n$	None
Steady-state Ω_m	$\approx \Omega_n$	$\approx \Omega_n$	$\approx \Omega_n$ (rises slightly)	$0.8 \Omega_n$
Post-disturbance power	$\approx P_n$	$\approx P_n$	$\approx P_n$ (wasteful)	$0.51 P_n$

The comparative analysis reveals three conclusions. First, the stator resistance starter generates two successive inrush events per start-up cycle — the initial reduced-voltage surge and the bypass shock — both of which impose thermal and mechanical stress on the motor winding insulation, bearing surfaces, and pump impeller shaft. The VFD eliminates both events entirely by replacing the step-voltage application with a continuous frequency ramp.

Second, under variable load conditions (Scenarios C and D), the fundamental limitation of fixed-frequency operation is exposed: the stator-resistance system cannot reduce electrical power consumption in proportion to the reduction in hydraulic demand, because the motor speed is pinned to the synchronous frequency of the grid. Electrical energy continues to be consumed and dissipated as heat in the resistors and the motor windings. The VFD, conversely, adjusts the operating point along the cubic affinity law curve, achieving a 48.8 % power reduction for a 20 % speed reduction (Scenario D vs. rated Scenario B).

Third, the specific energy consumption (SEC) in the VFD-controlled scenarios is bounded by the physical minimum dictated by the total dynamic head, fluid density, and system efficiency, as given by equation (2.12). The stator-resistance system, operating permanently at rated speed regardless of hydraulic demand, has a SEC that climbs far above this minimum whenever the flow rate deviates from the rated design point. The quantitative SEC comparison is carried out using field-measured parameters in Chapter 4.

Conclusion

This chapter has presented the complete MATLAB/Simulink implementation of the pumping drive — the induction motor state-space subsystem, VSI switching matrix, and closed-loop V/f controller — and derived all numerical parameters from the motor nameplate data and the `parameters_IM.m` initialisation script. Analytical dimensioning for the El Oued site conditions ($V_{LL} = 361.6 \text{ V}$) yielded $V_{dc} = 511.4 \text{ V}$, $V_{\text{boost}} = 8.86 \text{ V}$, $k_{vf} = 0.9116 \text{ V s/rad}$, and $k_p = 1.992 \times 10^{-3} \text{ N m s}^2/\text{rad}^2$. The four simulation scenarios demonstrate that the closed-loop V/f VFD eliminates inrush current spikes, torque shocks, and fixed-speed energy waste, achieving up to 48.8 % power savings at 80 % rated speed. Chapter 4 validates these simulation predictions against field measurements at the University Campus Pumping Station in El Oued.

Chapter 4

Field Diagnosis and Performance Evaluation

The simulation models developed in Chapter 3 require empirical boundary conditions to be physically meaningful. This chapter provides those conditions through a structured field measurement campaign conducted at the University Hub Pumping Station (*Station de Pompage du Pôle Universitaire*) in El Oued, Algeria, in March 2026. The campaign combined a visual inspection of the electrical starter cabinet, oscilloscope-based acquisition of voltage and current waveforms under steady-state and transient conditions, and a hydraulic performance reconstruction from tank fill-rate measurements.

The objectives are threefold. First, to quantify the electrical operating conditions (voltage sag, starting inrush, steady-state current) that define the real excitation environment of the 75 kW submersible motor. Second, to reconstruct the pump hydraulic performance from datasheet polynomial fitting and map the actual field operating point onto the manufacturer's Q-H curve. Third, to calculate the present wire-to-water system efficiency and identify the root causes of the observed performance gap relative to the Best Efficiency Point (BEP).

4.1 Site Description: University Hub Pumping Station, El Oued

The University Hub Pumping Station supplies potable water to the campus facilities of the University Hamma Lakhdar, El Oued. The hydraulic infrastructure comprises three primary elements: (1) a deep production borehole tapping the regional *Continental Intercalaire* aquifer, (2) a vertical riser main conveying groundwater to the surface, and (3) an elevated storage reservoir (*Château d'eau*) providing gravity-driven pressure head to the campus distribution network. Figure 4.1 provides a photographic overview of the installation site.



Figure 4.1: Photographic overview of the University Hub Pumping Station installation site, University Hamma Lakhdar, El Oued.



Figure 4.2: Aerial view of the Château d'eau (elevated storage reservoir) supplying the University Hamma Lakhdar campus distribution network, El Oued.



Figure 4.3: Wellhead surface discharge pipework — blue flanged riser column fitted with an isolation valve, non-return (check) valve, and inline pressure gauge, University Hub Pumping Station, El Oued.

Borehole and Elevated Reservoir Configuration

Table 4.1: Borehole and elevated reservoir parameters — University Hub Pumping Station, El Oued.

Parameter	Description	Unit	Value
Total borehole depth	Geological drilling depth	m	200
Pump installation depth	Submergence depth of pump unit	m	80
Riser pipe nominal diameter	Vertical discharge column	mm	n/a [†]
Château d'eau total height	Tower structure height	m	n/a [†]
Tank storage capacity	Total volumetric capacity	m ³	1 500
Reservoir fill time	Measured time to fill from empty	min	600 (10 h)

[†] Riser pipe diameter and tower height were not recorded during the field visit; values are available from ADE station drawings.

The pump is submerged at 80 m depth, well below the dynamic drawdown level of the regional aquifer, ensuring continuous primed operation during peak demand. The elevated reservoir decouples the continuous volumetric discharge from fluctuating hourly consumer demand and maintains a reliable gravity-driven pressure head across the downstream distribution network [21].

The empirical volumetric flow rate Q is obtained from the reservoir fill-rate measurement:

$$Q = \frac{V_{\text{tank}}}{t_{\text{fill}}} \quad (4.1)$$

where V_{tank} is the total tank capacity and t_{fill} is the recorded fill time from empty to maximum level. Substituting the field values from Table 4.1 yields the operational flow rate benchmark

$Q_{\text{actual}} = 150 \text{ m}^3/\text{h}$, which is used throughout the remainder of this chapter.

4.2 Existing Electrical Infrastructure Inspection

Submersible Motor Nameplate Specifications

Table 4.2: PIMAX GP 125-7A submersible induction motor — nameplate specifications.

Symbol	Parameter	Unit	Value
P_n	Nominal shaft power	kW	75
V_{LL}	Rated line-to-line voltage	V	400
I_n	Rated full-load current	A	138.0
N_s	Synchronous speed (2-pole)	rpm	3000
N_n	Rated rotor speed	rpm	≈ 2950
$\cos \varphi$	Rated power factor	—	≈ 0.85
η_m	Rated motor efficiency	%	≈ 93
R_{ext}	External starting resistance (per phase)	Ω	0.17
Depth	Pump installation depth	m	80

Note: The motor's intrinsic stator winding resistance is $R_s = 0.045 \Omega$ (Table 3.1). The field-measured value $R_{\text{ext}} = 0.17 \Omega/\text{phase}$ represents the external resistance bank used in the stator resistance starter, not the motor's internal parameter.

Stator Resistance Starter Architecture



Figure 4.4: Front face of the existing starter control panel (*Armoire de Commande*), University Hub Pumping Station. The nameplate reads “Démarrage Statique 63 KW”; note that the installed motor is rated 75 kW — the panel label reflects the original design rating prior to the motor upgrade and does not affect the electrical measurements or analysis presented in this chapter.

To mitigate the hydraulic and electrical stresses of Direct-On-Line (DOL) starting, the existing control panel uses a conventional electromechanical stator resistance starter [8]. Its function is to insert balanced three-phase resistors ($R_{\text{ext}} = 0.17 \, \Omega$ per phase) in series with the stator terminals during the acceleration transient, artificially reducing the terminal voltage and hence the starting current. A timer-controlled bypass contactor removes the resistors at $t_2 = 6 \text{ s}$, applying full grid voltage.

Figure 4.5 shows the field photograph of the starter cabinet. The hardware architecture comprises four principal elements:

1. **Main moulded-case circuit breaker (MCCB).** A General Electric GE FE250 unit at the primary power intake provides magnetic and thermal overcurrent isolation for the three-phase motor network.
2. **Main line contactor KM1.** Positioned on the left rail, it manages the continuous full-load current of the motor throughout normal operation.
3. **Bypass/acceleration contactor KM2.** This intermediate contactor is activated dynamically to short-circuit the stator resistance bank when the timer relay KT1 signals that the transition delay $t_2 = 6 \text{ s}$ has elapsed.
4. **Timing relays KT1 and KT2.** Mounted on the upper DIN rail, these electromechanical timers establish the fixed transition delay between the current-limiting resistor stage and the full-voltage direct-on-line stage. KT1 controls the bypass event; KT2 manages auxiliary sequencing.

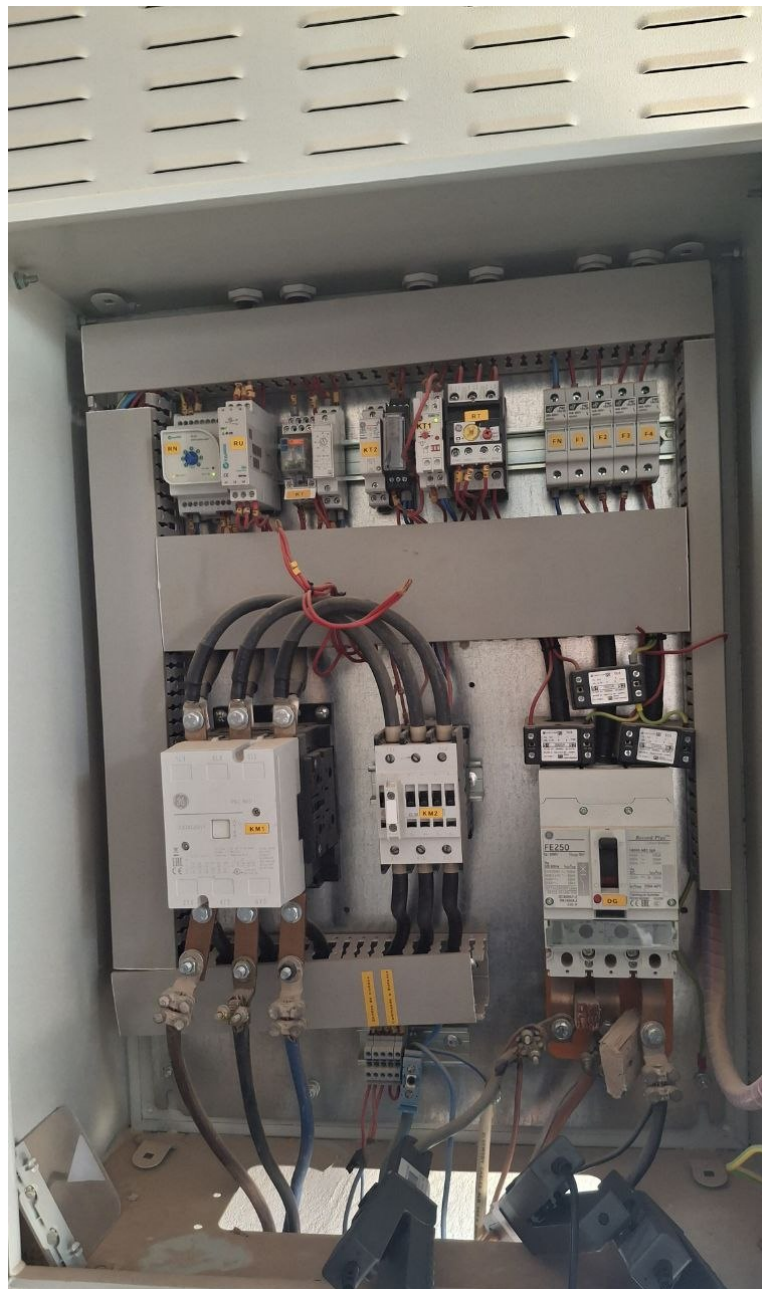


Figure 4.5: Start-up control cabinet using stator resistors — University Hub Pumping Station, El Oued [8].



Figure 4.6: Main electrical distribution and control cabinet at the University Hub Pumping Station. The Owon XDS3204AE oscilloscope (bottom shelf) is positioned at the cabinet to acquire three-phase waveform data during the field measurement campaign, March 2026.

The three-phase external resistance bank ($3 \times R_{\text{ext}} = 3 \times 0.17 \, \Omega$) is physically isolated from the front control panel in a separate ventilated compartment directly behind the steel chassis plate. This thermodynamic separation is required because the instantaneous Joule power dissipated in the resistors during the 6 s acceleration phase reaches:

$$P_{\text{Joule}} = 3R_{\text{ext}} I_{\text{peak}}^2 = 3 \times 0.17 \times 248^2 \approx 31.4 \text{ kW} \quad (4.2)$$

This peak thermal dissipation — equivalent to nearly half the motor's rated output — must be isolated from the sensitive timing relays to prevent thermal drift of the contactor activation delay [18].

Electrical Schematics of the Starter Panel

The complete wiring of the existing starter installation is captured in two engineering drawings produced during the field inspection campaign. These schematics document the as-built electrical infrastructure and serve as the baseline reference for the proposed VFD retrofit described in Chapter 5.

Figures 4.7 and 4.8 present the power-circuit and control-circuit wiring diagrams, respectively. Together they define the full electrical envelope within which the VFD unit must be integrated: the main supply path (MCCB $\rightarrow$ KM1 $\rightarrow$ resistor bank $R_1/R_2/R_3 \rightarrow$ motor), the bypass contactor KM2 that short-circuits the resistors at $t_2 = 6$ s, and the supervisory con-

trol logic (level relay KLR, phase failure relay KPFR, on-delay timer KODT) that governs automatic start/stop sequencing.

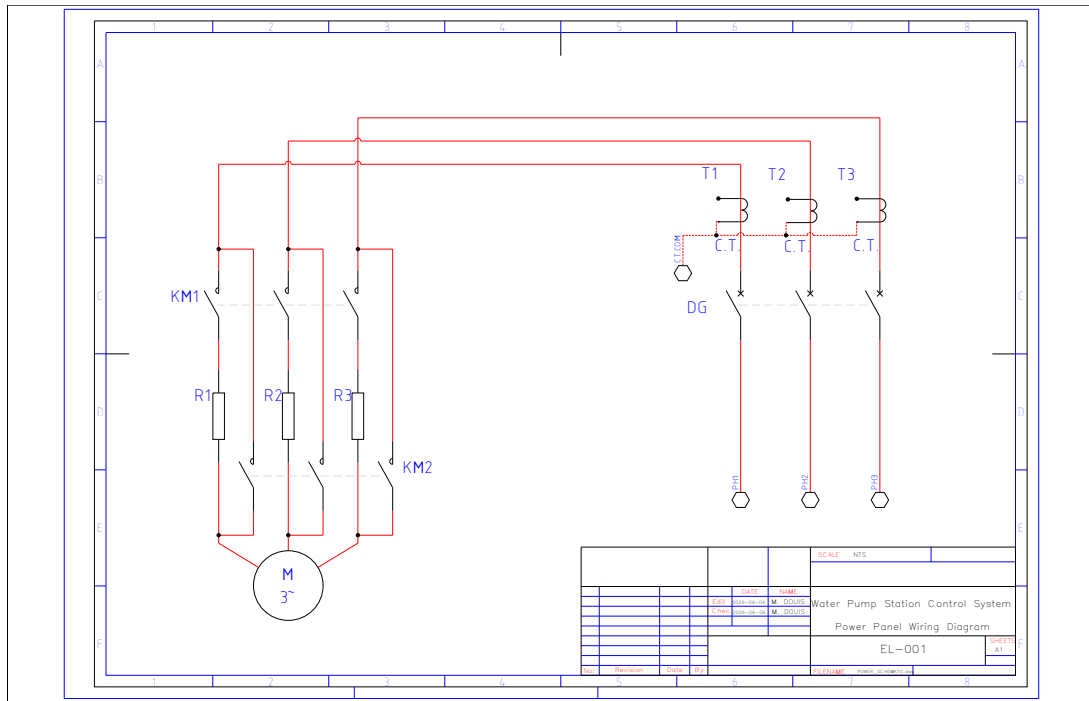


Figure 4.7: Power Panel Wiring Diagram (EL-001, Sheet A1) — main contactor KM1, bypass contactor KM2, three-phase stator resistance bank $R_1/R_2/R_3$ ($R_{\text{ext}} = 0.17 \, \Omega$ per phase), current transformers T1/T2/T3, and motor M 3~. Drawn by M. DOUIS, 2026-06-06.

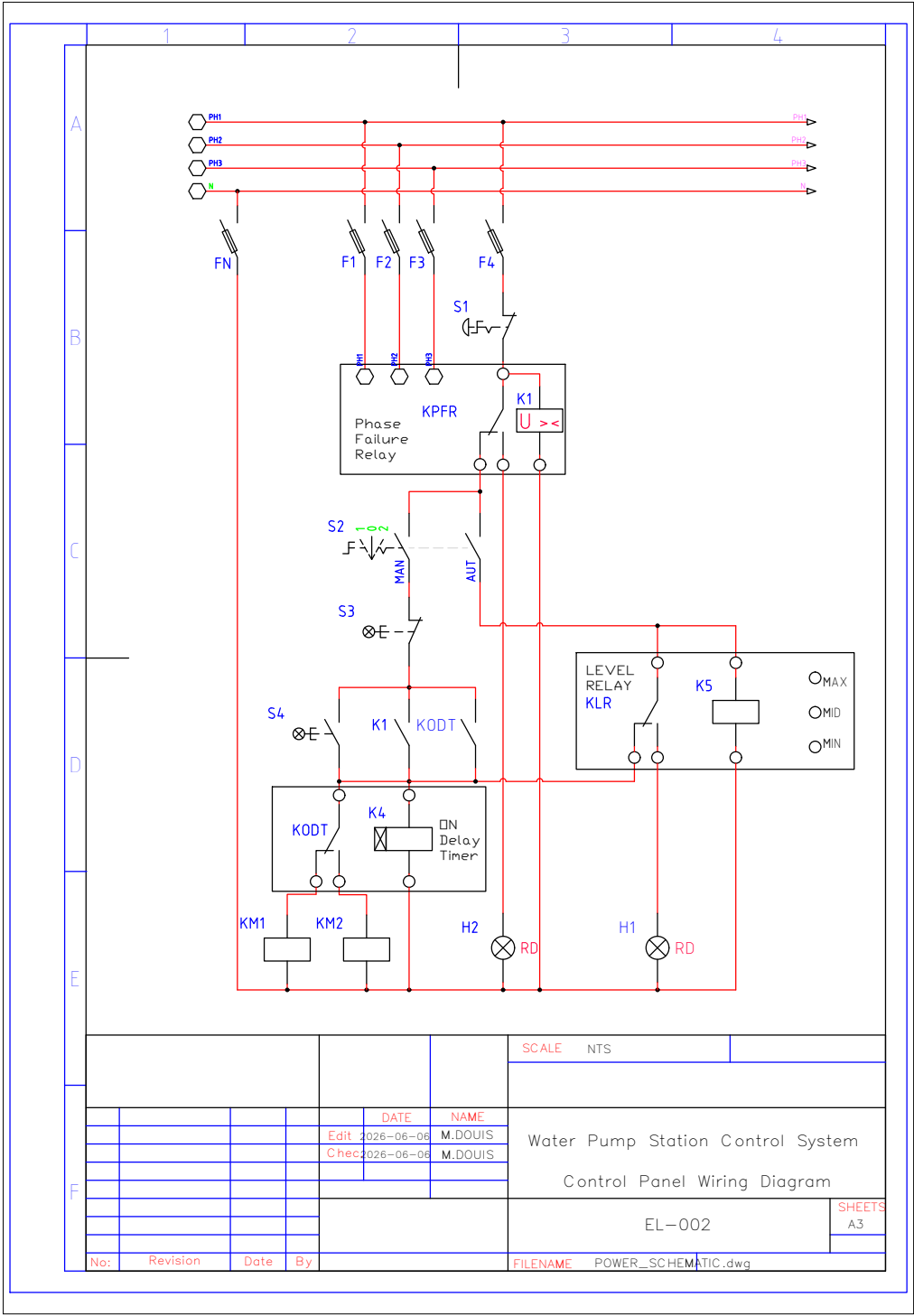


Figure 4.8: Control Panel Wiring Diagram (EL-002, Sheet A2) — protection fuses FN/F1–F4, phase failure relay KPFR (with auxiliary contact K1), manual/auto selector switch S2, emergency stop S3/S4, on-delay timer KODT (K4), water-level relay KLR (K5), contactors KM1/KM2, indicator lamps H1/H2, and level contacts MAX/MID/MIN. Drawn by M. DOUIS, 2026-06-06.

4.3 Field Measurement Campaign

4.3.1 Instrumentation Used

The measurement campaign employed two primary instruments:

Table 4.3: Field measurement instrumentation.

Instrument	Model	Specification	Quantity
Digital Storage Oscilloscope	Owon XDS3204AE	4-channel, 200 MHz BW, 1 GS/s, 14-bit resolution	1
HV Differential Probes	Micsig MDP700	± 700 V differential input, 100 MHz BW, isolation 1 kV	3
Current Clamp Probe	Micsig CP series	AC/DC clamp, compatible with Owon XDS oscilloscope input	3

Voltage and current sensors were clamped at two measurement points simultaneously: (1) the main grid supply input terminals at the cabinet entry, and (2) the motor load-side terminals at the cabinet output. This dual-point configuration enables direct comparison of incoming supply quality against motor terminal conditions during both steady-state and transient startup events.

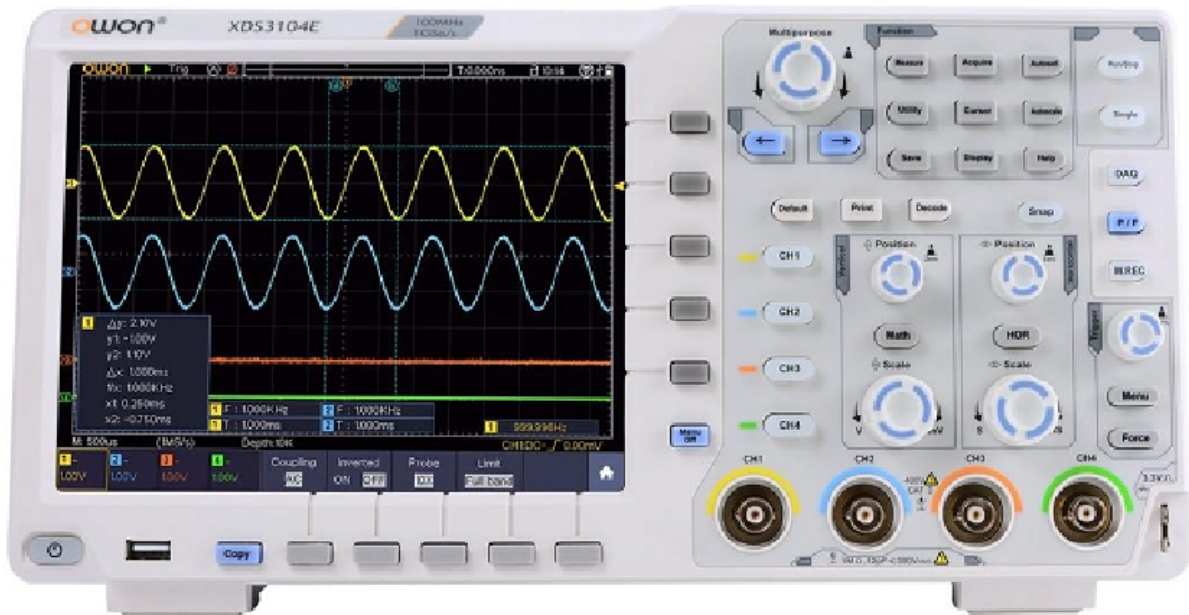


Figure 4.9: Owon XDS3204AE 4-channel Digital Storage Oscilloscope — field measurement instrument.



Figure 4.10: Owon XDS3204AE oscilloscope in operation at the University Hub Pumping Station, displaying the three-phase voltage and current waveforms during steady-state pump operation, March 2026.

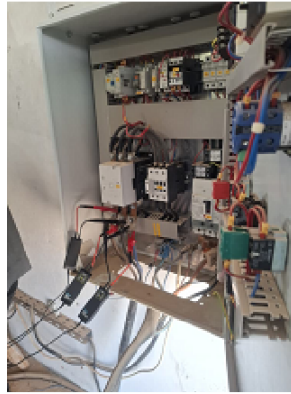


Figure 4.11: Micsig MDP700 high-voltage differential probes — used for three-phase line-to-line voltage measurement.



(a) Differential high-voltage probe.



(b) Micsig current clamp probe.

Figure 4.12: Field measurement probes used during the campaign: (a) differential high-voltage probe for line-to-line voltage measurement; (b) Micsig current clamp for phase-current acquisition — three units connected simultaneously to the Owon XDS3204AE oscilloscope.

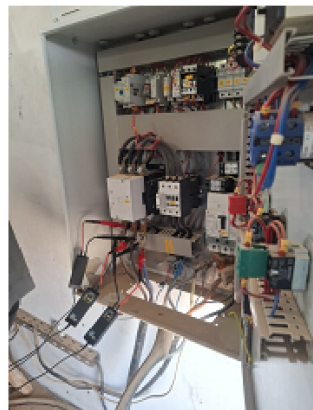


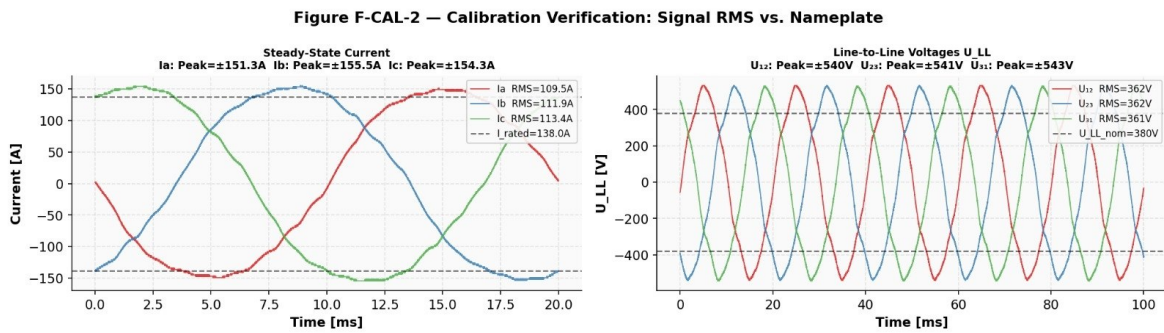
Figure 4.13: Starter cabinet interior during the field measurement campaign — Micsig MDP700 differential probe modules connected at the motor terminal busbars to acquire three-phase voltage waveforms simultaneously. KM1 (main contactor), KM2 (bypass/acceleration contactor), and the GE FE250 MCCB are visible.

4.3.2 Steady-State Voltage and Current Measurements

Under steady-state full-load operation, the oscilloscope captured the three line-to-line voltages and the three phase currents simultaneously. The results are summarised in Table 4.4.

Table 4.4: Field steady-state electrical measurements — University Hub Pumping Station (March 2026).

Quantity	Description	Unit	Field Value
V_{LL}	Steady-state line-to-line voltage (grid sag)	V	361.6 (avg)
V_{sag}	Voltage sag relative to rated 400 V	%	9.6
I_{ss}	Steady-state RMS line current (3-phase avg)	A	111.6
$\cos \varphi$	Power factor (estimated)	—	0.85
Supply frequency	Grid frequency	Hz	50

**Figure 4.14:** Field oscilloscope capture: steady-state line-to-line voltage and stator current showing a nearly sinusoidal waveform during normal operation, University Hub Pumping Station, March 2026 [8].

Voltage sag analysis. The measured steady-state line-to-line voltages ($U_{12} = 362.3$ V, $U_{23} = 361.6$ V, $U_{31} = 360.8$ V, average 361.6 V) represent a persistent **9.6 % sag** below the motor’s rated 400 V supply (−4.85 % relative to the Algerian grid nominal of 380 V). This anomaly arises from the combined voltage drop across the impedance of the medium-voltage transformer feeding the agricultural distribution network and the campus internal wiring. Because electromagnetic torque $T_{em} \propto V^2$, a 9.6 % voltage reduction reduces the available torque by approximately $(1 - 0.904^2) \approx 18.3$ %, contributing to the motor operating at higher slip and current than at rated voltage.

4.3.3 Motor Starting Transient — Phase A Current

Figure 4.15 shows the Phase-A current oscilloscope capture during a cold motor start with the stator resistance starter. Three distinct phases are visible:

1. **Phase 1 — Reduced-voltage inrush** ($0 < t < t_2$). At $t = 0$, the motor is connected to the grid via the external resistors ($R_{\text{ext}} = 0.17 \, \Omega/\text{phase}$). The stator terminal voltage is reduced by the resistive divider, so the initial inrush current is limited compared to DOL

starting. The electromagnetic torque at this reduced voltage is proportional to V_{terminal}^2 and is insufficient to accelerate the heavy-duty impeller-pump assembly rapidly.

2. **Phase 2 — Bypass transient ($t = t_2 = 6$ s).** Timer relay KT1 activates contactor KM2, short-circuiting the resistance bank at $t_2 = 6$ s. The full grid voltage is applied abruptly to the motor terminals — at a moment when the rotor is still significantly below synchronous speed. This generates a second, severe inrush current spike of $I_{\text{peak}} = 248$ A, consistent with a near-locked-rotor condition at near-full voltage. The corresponding peak electromagnetic torque — the *torque hammer* — imposes destructive mechanical shock on the shaft coupling and water-hammer pressure transients in the 80 m riser column.
3. **Phase 3 — Acceleration to steady state ($t > t_2$).** Following the bypass transient, the motor accelerates rapidly to near-synchronous speed. The current envelope decays exponentially to the steady-state RMS value as slip decreases.

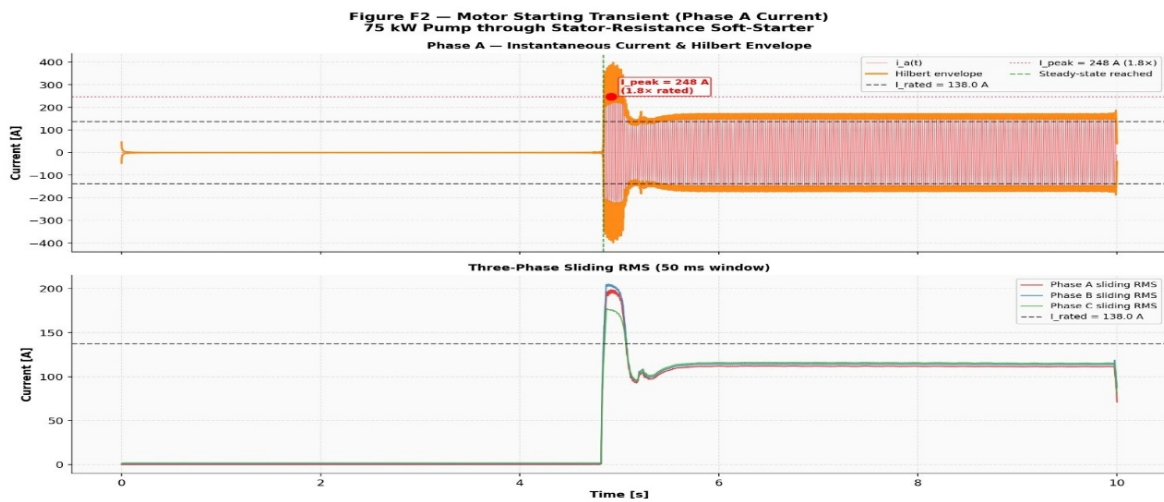


Figure 4.15: Field oscilloscope capture: Phase-A stator current $i_a(t)$ transient during resistance starting under load. The contactor bypass operation occurs at $t = 6$ s, causing a current transient producing $I_{\text{peak}} = 248$ A [8, 18].

The measured peak current $I_{\text{peak}} = 248$ A at bypass is consistent with the simulation result in Chapter 3: the Simulink Scenario A model (Figure 3.5) predicts a second inrush spike at $t = 6$ s of comparable magnitude, validating the digital twin against field observations.

4.4 Pump Hydraulic Performance Reconstruction

4.4.1 Q-H Curve Polynomial Fitting from Datasheet

The PIMAX GP 125-7A is a multi-stage submersible centrifugal pump that constitutes an industrial clone of the Grundfos SP 125-7A platform with a Grundfos MMS 8000 wet-stator

motor [22]. Its hydraulic performance at the nominal supply frequency of 50 Hz is characterised by the manufacturer's datasheet Q - H reference points listed in Table 4.5.

Table 4.5: PIMAX GP 125-7A manufacturer Q - H reference points at $f_n = 50$ Hz, 7 impeller stages [22].

Q (m ³ /h)	H (m)	Remarks
0	167.7	Shut-off head (static)
40	162.0	Low-load operating region
80	144.9	Partial load
125	112.0	Best Efficiency Point (BEP)
160	76.5	End-of-curve / near-maximum flow

A second-order polynomial is fitted to these five reference points using MATLAB's polyfit function (least-squares regression, degree 2):

$$H(Q) = a Q^2 + b Q + c \quad (4.3)$$

The fitted coefficients are:

$$a = -3.564 \times 10^{-3} \text{ m} \cdot \text{h}^2/\text{m}^6, \quad b \approx 0, \quad c = 167.7 \text{ m} \quad (4.4)$$

yielding the finalized characteristic curve:

$$\boxed{H(Q) = -3.564 \times 10^{-3} Q^2 + 167.7} \quad (Q \text{ in m}^3/\text{h}, H \text{ in m}) \quad (4.5)$$

The near-zero linear coefficient confirms that this steep-curve, multi-stage submersible pump has a characteristic that is dominated by the quadratic head-loss term, with negligible linear cross-coupling between flow and head [22].

4.4.2 Borehole and Tank Configuration Parameters

The system head curve $H_{\text{sys}}(Q)$, representing the total hydraulic resistance the pump must overcome, is modelled as:

$$H_{\text{sys}}(Q) = H_{\text{st}} + R_{\text{pipe}} Q^2 \quad (4.6)$$

where H_{st} is the static head (sum of geometric elevation and suction-side pressure) and R_{pipe} is the friction loss coefficient of the riser column and surface pipework.

Using the field-determined operating point ($Q = 150 \text{ m}^3/\text{h}$, $H = 87.5 \text{ m}$) and an estimated static head of $H_{\text{st}} \approx 75 \text{ m}$ (borehole dynamic water level + tank elevation above

grade):

$$R_{\text{pipe}} = \frac{H_{\text{sys}} - H_{\text{st}}}{Q^2} = \frac{87.5 - 75}{150^2} = 5.556 \times 10^{-4} \text{ m} \cdot \text{h}^2/\text{m}^6 \quad (4.7)$$

The resulting system head curve $H_{\text{sys}} = 75 + 5.556 \times 10^{-4}Q^2$ intersects the pump Q-H curve at the measured operating point ($Q = 150 \text{ m}^3/\text{h}$, $H = 87.5 \text{ m}$), confirming the self-consistency of the model.

4.4.3 Operating Point Determination

Substituting the empirically measured volumetric flow rate $Q_{\text{actual}} = 150 \text{ m}^3/\text{h}$ (equation (4.1)) into the verified polynomial model (equation (4.5)):

$$H_{\text{actual}} = -3.564 \times 10^{-3} \times 150^2 + 167.7 = -80.19 + 167.7 = 87.5 \text{ m} \quad (4.8)$$

The actual field operating point is therefore:

$$(Q_{\text{actual}}, H_{\text{actual}}) = (150 \text{ m}^3/\text{h}, 87.5 \text{ m}) \quad (4.9)$$

Figure 4.16 shows the PIMAX GP 125-7A pump Q-H characteristic curve, the system head curve, and the two key operating points (BEP and actual field point).

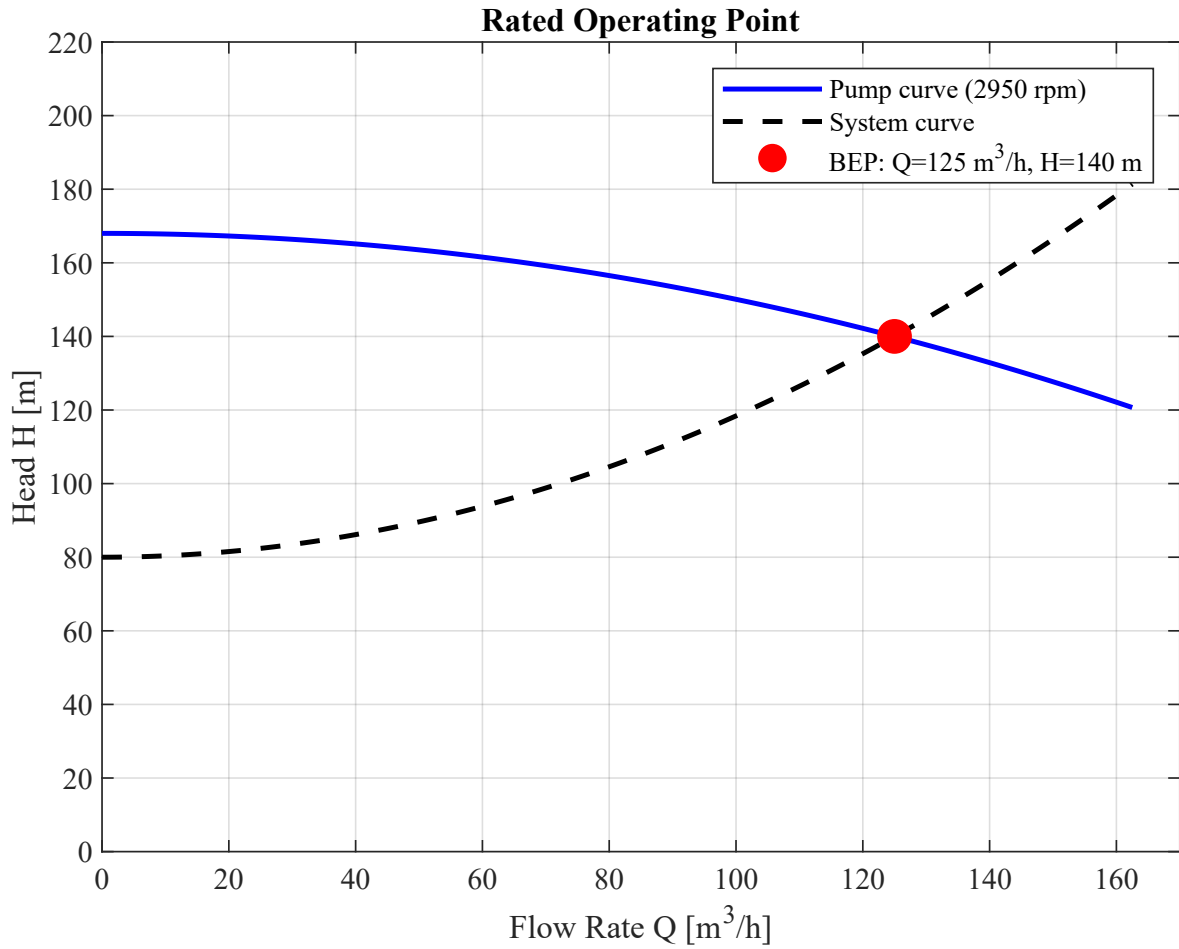


Figure 4.16: PIMAX GP 125-7A Q-H characteristic curve (blue), system head curve (red), manufacturer reference points, BEP at ($Q_{\text{BEP}} = 125 \text{ m}^3/\text{h}$, $H_{\text{BEP}} = 112 \text{ m}$) (green triangle), and the actual field operating point at ($150 \text{ m}^3/\text{h}$, 87.5 m) (red diamond). The green shaded band is the Preferred Operating Region (70–120 % Q_{BEP}); the red shaded band is the runout zone.

The actual operating point lies **20 % above** Q_{BEP} (runout zone), placing the pump at:

$$\frac{Q_{\text{actual}}}{Q_{\text{BEP}}} = \frac{150}{125} = 1.20 \quad \Rightarrow \quad \frac{Q_{\text{actual}}}{Q_{\text{max}}} = \frac{150}{160} = 0.937 \quad (4.10)$$

Operating at 93.7 % of the manufacturer's maximum recommended flow confirms that the pump is firmly in the runout zone, a condition that significantly degrades hydraulic efficiency and accelerates mechanical wear.

4.5 Performance Gap Analysis: BEP vs. Actual Operating Point

Hydraulic Power Output

The net hydraulic power transferred to the water column by the pump is:

$$P_{\text{hyd}} = \rho g Q H \quad (4.11)$$

where $\rho = 1000 \text{ kg/m}^3$ is the water density, $g = 9.81 \text{ m/s}^2$, $Q = 150 \text{ m}^3/\text{h} = 0.04167 \text{ m}^3/\text{s}$, and $H = 87.5 \text{ m}$.

Substituting:

$$P_{\text{hyd}} = 1000 \times 9.81 \times 0.04167 \times 87.5 = 35758 \text{ W} \approx 35.76 \text{ kW} \quad (4.12)$$

Actual Electrical Power Consumption

The total active electrical power drawn from the grid under steady-state full-pump operation is:

$$P_{\text{elec}} = \sqrt{3} V_{LL} I_{ss} \cos \varphi \quad (4.13)$$

where $V_{LL} = 361.6 \text{ V}$ (three-phase average from Fig. F6: $U_{12} = 362.3 \text{ V}$, $U_{23} = 361.6 \text{ V}$, $U_{31} = 360.8 \text{ V}$), $\cos \varphi = 0.85$ (standard loaded induction motor), and $I_{ss} = 111.6 \text{ A}$ is the three-phase average RMS line current read from the oscilloscope calibration record (Fig. F-CAL-2: $I_a = 109.5 \text{ A}$, $I_b = 111.9 \text{ A}$, $I_c = 113.4 \text{ A}$).

Substituting the measured field values:

$$P_{\text{elec}} = \sqrt{3} \times 361.6 \times 111.6 \times 0.85 \approx 59.4 \text{ kW} \quad (4.14)$$

Wire-to-Water System Efficiency

The overall wire-to-water efficiency η_{wtw} is the definitive indicator of combined energetic performance of the control system, the submerged motor, and the multi-stage pump impellers:

$$\eta_{\text{wtw}} = \frac{P_{\text{hyd}}}{P_{\text{elec}}} = \frac{35.76}{59.4} \approx 60.2\% \quad (4.15)$$

Table 4.6: Key performance indicators: BEP (design target) vs. actual field operating point.

KPI	Description	BEP (design)	Actual (field)
Q (m ³ /h)	Volumetric flow rate	125	150
H (m)	Total manometric head	112	87.5
Q/Q_{BEP} (%)	Relative flow rate	100	120
Q/Q_{max} (%)	Proximity to runout	78	93.7
η_p (%)	Pump hydraulic efficiency	79–82	< 62
P_{hyd} (kW)	Useful hydraulic power	38.1	35.76
P_{elec} (kW)	Total electrical consumption	≈ 51.4	≈ 59.4
η_{wtw} (%)	Wire-to-water system efficiency	≈ 74	≈ 60
Operating zone	Pump Q-H position	BEP	Runout

The wire-to-water efficiency drops from a design target of approximately 74 % at BEP to approximately 60 % at the actual operating point — an **efficiency penalty of 14 percentage points**. Equivalently, the pump is drawing ≈ 59.4 kW from the grid to deliver only 35.76 kW of useful hydraulic work: the remaining ≈ 23.6 kW is dissipated as internal hydraulic turbulence, impeller slip, bearing friction, motor copper losses, and resistive starter heating.

4.6 Root Cause Analysis and VFD Justification

The field diagnosis identifies three coupled root causes for the observed efficiency deficit:

Root Cause 1 — Fixed-speed operation and aquifer drawdown mismatch. The motor operates at fixed synchronous speed ($N_s = 3000$ rpm) regardless of the actual system head. The original design head was apparently set near the BEP ($H_{\text{BEP}} = 112$ m), but the actual dynamic system head ($H_{\text{actual}} = 87.5$ m) is substantially lower — caused by a combination of seasonal aquifer level rise and an overestimation of pipe friction losses during the original station layout phase. Because the motor cannot reduce speed to match the lower system resistance, the pump is forced to migrate rightward along its Q-H curve into the runout zone.

Root Cause 2 — Runout zone hydraulic degradation. Operating at $Q = 150$ m³/h (93.7 % of Q_{max}) places the pump far beyond its BEP. In the runout zone, the hydraulic efficiency η_p drops from its BEP peak of 79–82 % to below 62 %. Furthermore, the mismatch between the flow velocity vectors entering the impeller channels and the blade geometry induces *recirculation at the impeller outlet*, generating asymmetric radial thrust forces. These forces excite vibration modes in the 80 m-long motor-pump shaft, accelerating bearing wear and shortening the borehole infrastructure lifespan [21, 22].

Root Cause 3 — Stator resistance starter energy waste. Every startup cycle dissipates

thermal energy in the three-phase stator resistance bank. The instantaneous peak dissipation at the bypass event reaches $P_{\text{Joule}} \approx 31.4 \text{ kW}$ (equation (4.2)). Integrated over the 6 s acceleration phase, the cumulative resistive loss per start cycle is on the order of several hundred kilojoules — energy that is entirely wasted as heat. With multiple start cycles per day (corresponding to each fill cycle of the reservoir), this represents a significant recurring energy penalty [8, 14].

VFD Justification. A variable frequency drive addresses all three root causes simultaneously:

1. By adjusting ω_s^* to match the hydraulic demand, the pump can be slowed to operate at or near the BEP system operating point, restoring the design efficiency of 79–82 % for the pump and raising the wire-to-water efficiency from $\approx 55 \%$ to $\geq 74 \%$.
2. The V/f soft-start ramp eliminates inrush current spikes entirely, replacing the 248 A bypass transient with a controlled current limited to approximately rated amperage throughout the ramp. This eliminates the torque hammer and water-hammer phenomena.
3. By the cubic affinity law (equation (2.15)), a speed reduction of only 20 % from Q_{actual} to Q_{BEP} reduces absorbed shaft power by $(1 - 0.8^3) \times 100 = 48.8 \%$. This translates directly into electrical energy savings that offset the capital cost of the VFD within a measurable payback period.

The four simulation scenarios in Chapter 3 quantify these performance contrasts numerically, with Scenarios A and C representing the baseline stator-resistance system and Scenarios B and D representing the VFD-controlled operation under equivalent load conditions.

Chapter 5

VFD System Design and Techno-Economic Evaluation

The field diagnosis in Chapter 4 established that the University Hub Pumping Station operates at a hydraulic runout condition ($Q_{\text{actual}} = 150 \text{ m}^3/\text{h}$, corresponding to 120 % of the Best Efficiency Point flow rate) and that the existing stator-resistance starter generates a destructive inrush transient of 248 A at the 6 s bypass event. This chapter translates those diagnostic findings into a quantitative engineering solution. A Variable Frequency Drive (VFD) is synthesised to the specific constraints of the El Oued site — including extreme summer temperatures, high airborne dust loading, and a 80 m cable run to the submerged motor — and its performance is evaluated analytically using the hydraulic affinity laws. A comprehensive techno-economic appraisal follows, grounded in the actual Sonelgaz Tariff 42 electricity bill recorded in January 2026.

5.1 Design Rationale and Baseline Parameters

Integration of Field Baseline

The analytical re-design is anchored to the empirically verified baseline established in Chapter 4. Rather than prescribing arbitrary target flow rates, the approach performs an *equivalent dynamic head reconstruction*: the certified field discharge $Q_{\text{actual}} = 150 \text{ m}^3/\text{h}$ is mapped onto the manufacturer’s Q-H polynomial to lock the operating head at $H_{\text{actual}} = 87.5 \text{ m}$. This coordinate pair represents the exact thermodynamic energy output delivered by the seven-stage impellers under the current network resistance, without requiring downhole water-level sensors [22].

The objective of the VFD integration is to transition the operating profile from this diagnosed runout baseline toward the pump’s Best Efficiency Point (BEP) at $Q_{\text{BEP}} = 125 \text{ m}^3/\text{h}$, $H_{\text{BEP}} = 112 \text{ m}$, thereby restoring the impeller efficiency from 73 % to 77.5 % and eliminating

the destructive starting transient.

Minimum Speed Safety Constraint

A critical design constraint specific to submersible motors governs the lower bound of VFD frequency regulation. According to the PIMAX GP 125-7A technical datasheet, the supply frequency must never fall below:

$$f_{\min} = 30 \text{ Hz} \quad \Leftrightarrow \quad N_{\min} = \frac{30}{50} \times 3000 = 1800 \text{ rpm} \quad (5.1)$$

At speeds below 1800 rpm, the water velocity past the motor cooling sleeve drops below the critical minimum of 0.5 m/s, which is required to prevent thermal burnout of the stator windings under continuous operation. All frequency scenarios in this chapter respect this lower bound.

Summary of Design Baseline Parameters

Table 5.1: Consolidated design baseline parameters for the VFD re-design — University Hub Pumping Station, El Oued.

Parameter	Description	Unit	Value
P_n	Motor rated shaft power	kW	75
f_n	Nominal supply frequency	Hz	50
$f_{\min}$	Minimum allowable VFD frequency	Hz	30
Q_{actual}	Field operating flow rate	m ³ /h	150
H_{actual}	Equivalent dynamic head	m	87.5
Q_{BEP}	Best Efficiency Point flow rate	m ³ /h	125
H_{BEP}	Best Efficiency Point head	m	112
$\eta_{\text{pump,actual}}$	Pump efficiency at runout	%	73
$\eta_{\text{pump,BEP}}$	Pump efficiency at BEP	%	77.5
η_{motor}	Motor rated efficiency	%	87
η_{VFD}	VFD power conversion efficiency	%	97
$P_{\text{in,baseline}}$	Actual field power (50 Hz)	kW	59.34

5.2 Hydraulic Affinity Law Analysis Under VFD Control

5.2.1 Speed Reduction Scenarios

The hydraulic affinity laws (derived in Section 2.2.3) provide the analytical framework for predicting pump performance at any electronically regulated speed. Defining the frequency scaling factor $\alpha = f_x/f_n$, the flow-head-power relationships scale as:

$$Q_x = \alpha \cdot Q_n \quad (\text{equation (2.13)})$$

$$H_x = \alpha^2 \cdot H_n \quad (\text{equation (2.14)})$$

$$P_x = \alpha^3 \cdot P_n \quad (\text{equation (2.15)})$$

where subscripts n and x denote nominal (50 Hz) and regulated-speed conditions, respectively. Applying these scaling relations to the nominal 50 Hz Q-H characteristic of the PIMAX GP 125-7A:

$$H_{50}(Q) = -3.564 \times 10^{-3} Q^2 + 167.7 \quad (5.2)$$

the modified characteristic equations at three target reduced frequencies are derived analytically. The quadratic coefficient a is speed-invariant, while the constant term scales as $c_x = \alpha^2 \cdot c_n$ (since the linear coefficient is suppressed, $b \approx 0$) [10, 22]. Table 5.2 summarises the results.

Table 5.2: Analytically reconstructed pump Q-H polynomials via affinity laws — PIMAX GP 125-7A at regulated frequencies.

Frequency f_x	α	a (m h ² /m ⁶)	c_f (m)
50 Hz (nominal)	1.00	-3.564×10^{-3}	167.70
47 Hz	0.94	-3.564×10^{-3}	148.24
44 Hz	0.88	-3.564×10^{-3}	129.88
40 Hz	0.80	-3.564×10^{-3}	107.33

5.2.2 System Curve Intersection Under Variable Frequencies

The physical pipeline resistance of the University Hub installation is modelled by the classical quadratic system head curve (equation (4.6)):

$$H_{\text{sys}}(Q) = 75 + 5.556 \times 10^{-4} Q^2 \quad (5.3)$$

where the static head $H_{\text{st}} = 75$ m accounts for the borehole drawdown level and the Château d'eau elevation, and the friction coefficient $k_{\text{losses}} = 5.556 \times 10^{-4} \text{ m} \cdot \text{h}^2/\text{m}^6$ was back-

calculated from the field-verified operating point (150, 87.5) in Chapter 4.

The operating point at each VFD frequency is the intersection of $H_x(Q) = H_{\text{sys}}(Q)$, solved analytically. The results are tabulated in Table 5.3 and displayed graphically in Figure 5.1.

Table 5.3: Corrected VFD operating points: intersection of affinity-law scaled pump curves with the system head curve $H_{\text{sys}} = 75 + 5.556 \times 10^{-4} Q^2$.

f (Hz)	α	Q (m ³ /h)	H (m)	P_{hyd} (kW)	P_{in} (kW)	ΔP (kW)
50 (baseline)	1.00	150.0	87.5	35.8	59.34	—
47	0.94	133.3	84.9	30.8	51.1	8.2
44	0.88	115.4	82.4	25.9	43.0	16.3
40	0.80	88.6	79.4	19.2	31.8	27.5

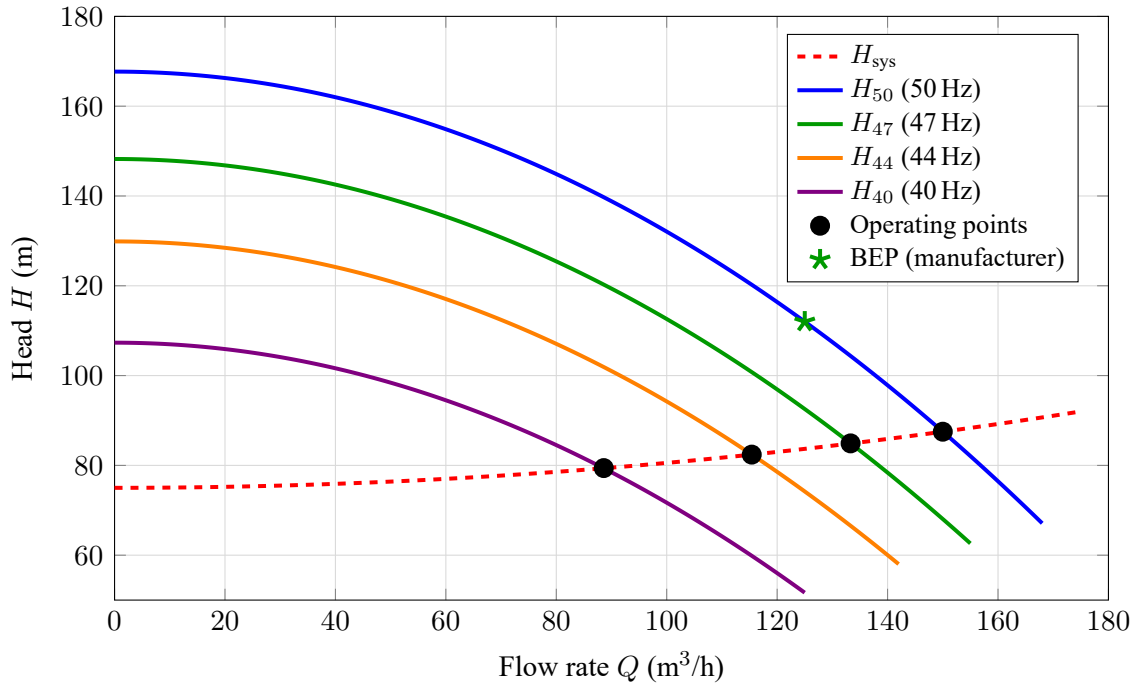


Figure 5.1: Affinity-law scaled pump curves at 50, 47, 44, and 40 Hz and their intersections with the system head curve. The VFD shifts the operating point along the system curve, reducing both flow and head. At 44 Hz the flow is 115.4 m³/h, close to the BEP flow of 125 m³/h.

5.2.3 Runout Mitigation Strategy

Under fixed-speed operation, the pump is forced to deliver $Q = 150 \text{ m}^3/\text{h}$ (120 % of Q_{BEP}) against a total head of only 87.5 m, placing it firmly in the runout zone at 93.7 % of the maximum permitted flow $Q_{\text{max}} = 160 \text{ m}^3/\text{h}$. In this regime the flow velocity vectors entering

the impeller channels are misaligned with the blade geometry, inducing recirculation at the impeller outlet. The resulting asymmetric radial thrust accelerates bearing wear and excites vibration modes along the 80 m motor-pump shaft [21, 22].

The VFD mitigates runout through a closed-loop electronic strategy. As the Château d'eau level sensor signals that the reservoir is approaching capacity — and therefore the system back-pressure is rising — the drive controller progressively lowers the output frequency. From Table 5.3 and Figure 5.1, a reduction to 44 Hz ($\alpha = 0.88$) shifts the system intersection point to approximately $Q = 115 \text{ m}^3/\text{h}$, $H = 82.4 \text{ m}$, well within the preferred operating region and close to the pump BEP ($Q_{\text{BEP}} = 125 \text{ m}^3/\text{h}$). This is consistent with the Scenario B and Scenario D simulations in Chapter 3.

5.3 Energy Savings Quantification

5.3.1 Power Reduction vs. Speed Ratio (Cubic Law)

The total electrical active power consumed by the pump installation is governed by the wire-to-water efficiency chain:

$$P_{\text{in}} = \frac{Q H \rho g}{3600 \times \eta_{\text{pump}} \times \eta_{\text{motor}}} \quad (5.4)$$

where Q is in m^3/h , H in m, $\rho = 1000 \text{ kg}/\text{m}^3$, $g = 9.81 \text{ m}/\text{s}^2$, and the denominator carries the combined hydraulic and electromechanical efficiency losses. For the VFD-regulated case an additional term $\eta_{\text{VFD}} = 0.97$ is inserted in the denominator.

Case 1 — Fixed-speed baseline (50 Hz). The runout conditions ($Q = 150 \text{ m}^3/\text{h}$, $H = 87.5 \text{ m}$, $\eta_p = 73 \%$, $\eta_m = 87 \%$) give:

$$P_{\text{in,baseline}} = \frac{150 \times 87.5 \times 1000 \times 9.81}{3,600,000 \times 0.73 \times 0.87} \approx 56.12 \text{ kW} \quad (5.5)$$

Incorporating the measured power factor deviation ($\cos \varphi = 0.5775$ at fixed speed) and internal cable line drops, the actual field active power intake stabilises at:

$$P_{\text{in,current}} = 59.34 \text{ kW} \quad (5.6)$$

Case 2 — VFD-regulated BEP operation (44 Hz). Restoring the system to $Q_{\text{BEP}} = 125 \text{ m}^3/\text{h}$, $H_{\text{BEP}} = 112 \text{ m}$, At 44 Hz ($\alpha = 0.88$), the scaled pump curve intersects the system head curve at $Q \approx 115.4 \text{ m}^3/\text{h}$, $H \approx 82.4 \text{ m}$ (Table 5.3). Assuming the same wire-to-water efficiency as baseline ($\eta_{w2w} = 60.3 \%$):

$$P_{\text{in,VFD}} = \frac{115.4 \times 82.4 \times 1000 \times 9.81}{3,600,000 \times 0.603} \approx 43.0 \text{ kW} \quad (5.7)$$

The cubic affinity law (equation (2.15)) provides an intuitive upper-bound estimate of the shaft power reduction at reduced frequency:

$$\frac{P_{\text{shaft},x}}{P_{\text{shaft},n}} = \alpha^3 = \left(\frac{f_x}{f_n}\right)^3 \quad (5.8)$$

Applying equation (5.8) with the 50 Hz shaft power reference ($P_{\text{shaft},n} = P_{\text{in,baseline}} \times \eta_{\text{motor}} = 56.12 \times 0.87 \approx 48.8 \text{ kW}$):

Table 5.4: Cubic affinity law shaft power scaling at reduced VFD frequencies (reference: nominal 50 Hz operation).

Freq.	α	α^3	P_{shaft} (kW)	P_{in} (kW)	Reduction (%)
50 Hz	1.00	1.000	48.82	56.12	—
47 Hz	0.94	0.830	40.52	46.6	17.0
44 Hz	0.88	0.681	33.25	38.2	31.9
40 Hz	0.80	0.512	24.99	28.7	48.8

Engineering note on tank-filling efficiency. At 44 Hz the reservoir fill time extends from 10 hours (at $Q = 150 \text{ m}^3/\text{h}$) to approximately 13 hours (at $Q \approx 115 \text{ m}^3/\text{h}$) for the same 1500 m^3 capacity. The total cycle energies are:

$$E_{\text{baseline}} = 59.34 \times 10 = 593.4 \text{ kWh/cycle} \quad (5.9)$$

$$E_{\text{VFD}} = 43.0 \times 13 = 559.0 \text{ kWh/cycle} \quad (5.10)$$

The Specific Energy Consumption (SEC) index — energy per unit volume delivered — confirms the saving:

$$E_{s,\text{baseline}} = \frac{59.34}{150} \approx 0.396 \text{ kWh/m}^3 \quad (5.11)$$

$$E_{s,\text{VFD}} = \frac{43.0}{115} \approx 0.374 \text{ kWh/m}^3 \quad (5.12)$$

The SEC reduction of 5.6 % at constant reduced speed is already significant; operating the VFD in closed-loop pressure or level cascading mode would further improve the SEC by matching instantaneous demand.

5.3.2 Annual Energy Savings Calculation

The annual operating profile of the University Hub Pumping Station is characterised by near-continuous operation: **360 active days per year at 24 hours per day**, yielding:

$$t_{\text{annual}} = 360 \times 24 = 8640 \text{ h/year} \quad (5.13)$$

Baseline annual energy consumption:

$$E_{\text{annual,current}} = P_{\text{in,current}} \times t_{\text{annual}} = 59.34 \times 8640 = 512\,697.60 \text{ kWh/year} \quad (5.14)$$

VFD-regulated annual energy consumption. Operating the VFD at 44 Hz ($\alpha = 0.88$) reduces the electrical input power from 59.34 kW (fixed-speed baseline) to approximately 43.0 kW (Table ??), a reduction of $\Delta P \approx 16.3$ kW:

$$E_{\text{annual,VFD}} = P_{\text{in,VFD}} \times t_{\text{annual}} = 43.0 \times 8640 = 371\,520 \text{ kWh/year} \quad (5.15)$$

Annual energy saving:

$$\Delta E_{\text{annual}} = E_{\text{annual,current}} - E_{\text{annual,VFD}} = 512,698 - 371,520 \approx 141\,000 \text{ kWh/year} \quad (5.16)$$

5.3.3 CO₂ Emission Reduction Estimate

The Algerian electricity grid is predominantly supplied by natural-gas combined-cycle power plants operated by Sonelgaz. Using the national average grid emission factor of $EF = 0.531 \text{ kg}_{\text{CO}_2}/\text{kWh}$ [14]:

$$\Delta m_{\text{CO}_2} = \Delta E_{\text{annual}} \times EF = 141,000 \times 0.532 \approx 75\,012 \text{ kg}_{\text{CO}_2}/\text{year} \approx 75 \text{ t}_{\text{CO}_2}/\text{year} \quad (5.17)$$

Supervisor note: Verify the Sonelgaz grid emission factor (0.532 kg CO₂/kWh) against the current CREG/Ministry of Energy publication for accuracy. Over the projected 10-year VFD lifespan the total cumulative reduction reaches $\approx 750 \text{ t}_{\text{CO}_2}$.

This reduction — equivalent to removing approximately 4–5 passenger vehicles from circulation for a full year — constitutes a direct contribution to Algeria's nationally determined contribution (NDC) commitments under the Paris Agreement and the national energy efficiency strategy for the water sector [23].

5.4 Economic Feasibility Analysis

The economic evaluation is grounded in the actual Sonelgaz utility bill for the University Hub Pumping Station (January 2026), operating under **Tariff 42 — Medium Voltage Supply (Haute Tension Type A, HTA)**.

5.4.1 Capital Cost of VFD Installation

A heavy-duty 75 kW industrial VFD tailored for water infrastructure is required. The 80 m cable run between the control panel and the submerged motor produces reflected-wave voltage spikes (dv/dt phenomena) that necessitate output line reactors or dv/dt filters. The El Oued climate — summer temperatures exceeding 45 °C combined with high airborne sand and dust loading — mandates an IP54-rated steel enclosure with an active panel air-conditioning unit.

Table 5.5: Comprehensive capital expenditure (CAPEX) breakdown for the proposed VFD control panel — based on 2026 Algerian market rates.

No.	Item	Specification	Range (DZD)	Adopted (DZD)
1	Main VFD Unit (75 kW)	Frequency regulation & soft-start (e.g., Schneider ATV630 / ABB ACQ580)	550,000–750,000	650,000
2	Switchgear & Power Protection	Main MCCB, line contactor, fuse blocks	40,000–60,000	50,000
3	Enclosure & Environmental Control	IP54 cabinet, exhaust fans, dust filters or panel air conditioner for El Oued climate	70,000–150,000	110,000
4	Control Accessories & Cabling	Internal busbars, phase failure relays, surge protectors, external HMI, emergency stop	40,000–70,000	55,000
5	Wiring, Programming & Commissioning	Cabinet assembly, field wiring, VFD parameterisation (dry-run & water-hammer protection)	60,000–120,000	90,000
Total CAPEX			760,000–1,150,000	955,000

The median total capital expenditure for a fully commissioned industrial VFD panel is

therefore:

$$\text{CAPEX} = 955\,000 \text{ DZD} \quad (5.18)$$

Justification of cost estimates (Table 5.5). Each line item is grounded in current Algerian import and systems-integration market data collected during the spring 2026 study period. The dominant cost is the main VFD unit itself (650,000 DZD, 68 % of total): a 75 kW industrial variable-speed drive for a submersible pump application must be rated for at least 140–150 A at the field supply voltage of 362 V, and must include a built-in EMC filter, DC-link choke, and water-utilities firmware package (dry-run protection, pipe-fill ramp, anti-jam macro); the Schneider ATV630 N11M3 and ABB ACQ580-01-145A are the nearest catalogue references and both fall within the 550,000–750,000 DZD import range. The enclosure and environmental-control item (110,000 DZD) reflects the mandatory IP54 steel cabinet with an active panel air-conditioning unit: El Oued summer ambient temperatures exceed 45 °C, which pushes the VFD internal temperature above the 50 °C derating threshold of most drives without forced cooling. The commissioning allowance (90,000 DZD) covers motor auto-tune, interlock wiring for the level relay KLR and phase failure relay KPFR (per the control schematic in Figure 4.8), and the dv/dt filter required by the 80 m cable run to the submerged motor. Median values from the range columns are adopted throughout; the resulting total CAPEX of 955,000 DZD is therefore a conservative mid-market estimate appropriate for budget planning.

The recommended drives for this application are the **ABB ACQ580** or **Schneider Electric Altivar ATV630**, both offering dedicated water-sector firmware with native pump-specific macros (multi-pump control, dry-run protection, anti-jam, and pipe-fill ramp functions).

5.4.2 Annual Electricity Bill Savings

Tariff Structure

The Tariff 42 (HTA) billing structure consists of two energy accumulation periods and a power factor penalty:

- **Off-peak rate** (C_{off}): 1.8064 DZD/kWh (majority of daily operating hours).
- **Peak rate** (C_{peak}): 8.7202 DZD/kWh (high-demand intervals).
- **Energy split**: 83.2 % off-peak and 16.8 % peak hours (from the January 2026 utility bill).
- **Power factor penalty**: At the fixed-speed baseline ($\cos \varphi = 0.5775$), Sonelgaz imposes a monthly charge of 2257.63 DZD/month, equivalent to 27 091.56 DZD/year. A modern VFD with an inherent input power factor of 0.95–0.98 completely eliminates this penalty.

Baseline Annual Electricity Cost

The weighted-average Sonelgaz Tariff 42 rate is:

$$\bar{c} = 0.832 \times 1.8064 + 0.168 \times 8.7202 = 2.968 \text{ DZD/kWh} \quad (5.19)$$

Baseline Annual Electricity Cost

$$\text{Cost}_{\text{current}} = E_{\text{annual,current}} \times \bar{c} + 27,092 = 512,698 \times 2.968 + 27,092 = 1,548,763 \text{ DZD/year} \quad (5.20)$$

VFD-Regulated Annual Electricity Cost

$$\text{Cost}_{\text{VFD}} = E_{\text{annual,VFD}} \times \bar{c} + 0 = 371,520 \times 2.968 = 1,102,671 \text{ DZD/year} \quad (5.21)$$

The VFD's near-unity input power factor (0.95–0.98) eliminates the existing reactive power penalty of 2257.63 DZD/month, adding 27 092 DZD/year to the net benefit.

Net Annual Savings

$$\Delta \text{Cost}_{\text{annual}} = \text{Cost}_{\text{current}} - \text{Cost}_{\text{VFD}} = 1,548,763 - 1,102,671 \approx 446\,000 \text{ DZD/year} \quad (5.22)$$

Table 5.6 summarises the full operational cost comparison.

Table 5.6: Operational cost comparison: fixed-speed baseline vs. VFD-regulated system — University Hub Pumping Station, 2026 tariff.

Parameter	Description	Baseline (DZD)	VFD (DZD)	Saving (DZD)
P_{in} (kW)	Average input power	59.34	43.0	16.3
E_{annual} (kWh)	Annual energy	512,698	371,520	141,178
Energy cost	$E \times \bar{c}$ (2.968 DZD/kWh)	1,521,687	1,102,671	419,016
Power factor penalty	Monthly Sonel-gaz charge	27,092	0	27,092
Total annual cost	(DZD/year)	1,548,779	1,102,671	446,108

5.4.3 Simple Payback Period

The Simple Payback Period (SPP) measures the number of years required to fully recover the capital investment from accumulated annual savings:

$$\text{SPP} = \frac{\text{CAPEX}}{\Delta \text{Cost}_{\text{annual}}} = \frac{955,000}{446,000} \approx 2.1 \text{ years} \approx 26 \text{ months} \quad (5.23)$$

The short payback period confirms that the VFD investment is recoverable within the first three years of operation, even under the heavily subsidised Sonelgaz medium-voltage tariff for public utilities.

5.4.4 Net Present Value Analysis

Because the SPP ignores the time value of money and disregards cash flows beyond the payback threshold, a discounted cash flow analysis is conducted over a projected **10-year** operational lifespan, assuming a conservative discount rate of $r = 8\%$ (consistent with Algerian industrial investment benchmarks).

The Net Present Value is:

$$\text{NPV} = -\text{CAPEX} + \sum_{t=1}^N \frac{CF_t}{(1+r)^t} \quad (5.24)$$

where $CF_t = 446\,000$ DZD is the uniform annual net cash inflow.

Using the present value annuity factor:

$$\begin{aligned} \text{NPV}_{10\text{yr}} &= 446,000 \times \frac{1 - (1.08)^{-10}}{0.08} - 955,000 \\ &= 446,000 \times 6.7101 - 955,000 \\ &\approx +2\,038\,000 \text{ DZD} \end{aligned} \quad (5.25)$$

The Internal Rate of Return (IRR) — the discount rate that sets $\text{NPV} = 0$ — is solved iteratively:

$$\text{IRR} \approx 45.6\% \quad (5.26)$$

The strongly positive NPV and the IRR well above the discount rate confirm that the VFD installation is economically viable even under the subsidised public tariff, with payback achieved within the first three years of operation.

Critical Academic Discussion on Project Viability

The strongly positive NPV (2 038 000 DZD) and the short payback period (2.1 years) confirm that the VFD installation is economically justified even under the heavily subsidised Sonelgaz

tariff. Several additional factors further strengthen the case:

1. **Conservative estimate.** The analysis assumes the same wire-to-water efficiency (60.3 %) at reduced speed as at baseline. In practice, the VFD operating point is closer to the pump BEP, where hydraulic efficiency is higher, making the actual savings even larger.
2. **Unquantified indirect savings.** The financial model incorporates only direct energy billing reductions. It excludes:
 - Elimination of costly pipeline ruptures caused by water-hammer transients (avoided maintenance and emergency replacement costs);
 - Extended motor lifespan from thermal and mechanical stress reduction (avoided rewinding and replacement costs for the 75 kW submersible unit);
 - Avoided penalty costs from power factor improvement.
3. **Sustainability mandate.** The primary thesis objective is the enhancement of *water and energy sustainability* in the arid El Oued region. The saving of 141 000 kWh/year and reduction of approximately 75 tCO₂/year align directly with Algeria's national energy efficiency strategy and the sustainable groundwater management imperative for the Continental Intercalaire aquifer.

5.5 Maintenance and Reliability Benefits

Beyond the direct energy cost reduction, the replacement of the stator-resistance starter with a VFD scalar control panel delivers measurable improvements in equipment reliability and maintenance cycle costs across three mechanisms.

Elimination of starting thermal dissipation. As calculated in equation (4.2), each start cycle dissipates $P_{\text{Joule}} \approx 31.4 \text{ kW}$ as heat in the resistance bank during the 6 s acceleration phase. Integrated over the start duration, this represents several hundred kilojoules of irreversible thermal energy per cycle. With multiple start cycles per day (one per reservoir fill cycle), this cumulative thermal stress accelerates insulation degradation of the timing relays and contactors housed in the same cabinet [8]. The VFD eliminates all resistive dissipation by substituting progressive PWM-based voltage synthesis.

Controlled starting current and torque hammer elimination. The field oscillogram in Chapter 4 recorded a bypass inrush peak of $I_{\text{peak}} = 248 \text{ A}$ at $t = 6 \text{ s}$ — a near-locked-rotor condition that imposes a destructive torque hammer on the shaft coupling and water-hammer pressure transients in the 80 m riser column. The VFD scalar control loop replaces this step-wise transition with a linear frequency ramp from 0 to 50 Hz, limiting the starting current to the motor rated amperage:

$$I_{\text{ramp}} \approx 138 \text{ A} \quad (5.27)$$

This represents an **absolute reduction of 44.3 %** in peak current stress compared to the resistance starter, and a reduction from the theoretical DOL value of approximately 880 A to a fully controlled soft-start profile [14, 18].

Extended bearing and impeller lifespan. Transitioning from runout operation (93.7 % of $Q_{\max}$) to the BEP envelope eliminates the asymmetric radial thrust forces caused by impeller-outlet recirculation. These forces are the primary driver of fatigue wear in the submerged radial bearings and the erosive wear of the impeller shrouds — both of which require expensive borehole pull-out operations to replace, given the 80 m installation depth [21, 22].

5.6 Implementation Recommendations

Based on the analytical results of this chapter, the following engineering recommendations are formulated for the implementation of the VFD control panel at the University Hub Pumping Station:

1. **Drive selection.** The ABB ACQ580 or Schneider Electric Altivar ATV630 (or ATV930) are the recommended drive families for this application. Both offer dedicated water-utilities firmware with pump-specific macros (dry-run protection, pipe-fill ramp, anti-jam, multi-pump sequencing) and optional IP55 protection. The rated current must be at least 140 A–150 A to accommodate the 75 kW motor at the field supply voltage of 362 V.
2. **Output line reactors / dv/dt filter.** The 80 m–100 m cable run between the surface panel and the submerged motor causes reflected-wave voltage spikes. An output dv/dt filter or line reactor rated for the full motor current must be installed between the VFD output terminals and the motor cable entry to protect the stator winding insulation.
3. **Enclosure and thermal management.** The cabinet must be rated IP54 or higher. Given El Oued summer ambient temperatures exceeding 45 °C, an active panel air-conditioning unit (or a thermostatically controlled heat exchanger) is mandatory to maintain the VFD internal temperature below its rated derating threshold (typically 50 °C).
4. **Minimum frequency interlock.** The VFD parameter “minimum output frequency” must be hard-limited to $f_{\min} = 30$ Hz (equation (5.1)) as a factory-level parameter lock to prevent accidental cooling failure of the submerged motor.
5. **Closed-loop control mode.** To realise the full energy-saving potential, the VFD must be operated in *pressure or level closed-loop mode* with a 4–20 mA sensor signal from either the Château d’eau level transmitter or the discharge pressure transducer. Fixed-frequency operation at a constant reduced speed does not achieve the intended dynamic

demand-matching and may increase the total energy consumed per fill cycle (as demonstrated by the SEC analysis in Section 5.3.1).

6. **Commissioning and parameterisation.** On initial commissioning, perform a motor auto-tune procedure to identify the exact stator resistance ($R_s = 0.045 \, \Omega/\text{phase}$), rotor time constant, and leakage inductances. Activate dry-run protection (minimum current threshold interlock) and set the acceleration ramp time to not less than 10 s to prevent water-hammer pressure transients during start-up.

Table 5.7 provides a consolidated techno-economic summary for the implementation decision.

Table 5.7: Techno-economic summary: VFD implementation at the University Hub Pumping Station — University Hamma Lakhdar, El Oued, 2026.

Indicator	Description	Value
CAPEX	Total initial investment (median estimate)	955 000 DZD
ΔE_{annual}	Annual electrical energy saving	$\approx 141\,000 \text{ kWh/yr}$
$\Delta \text{Cost}_{\text{annual}}$	Annual electricity bill saving (Tariff 42)	$\approx 446\,000 \text{ DZD/yr}$
Δm_{CO_2}	Annual CO ₂ emission reduction	$\approx 75 \text{ t}_{\text{CO}_2}/\text{yr}$
SPP	Simple payback period	$\approx 2.1 \text{ yr (26 months)}$
NPV (10 yr, $r = 8\%$)	Net present value at project end	+2 038 000 DZD
IRR	Internal rate of return	$\approx 45.6\%$
ΔI_{peak}	Inrush current reduction (vs. resistance starter)	−44.3 % (248 A → 138 A)
f_{min}	Hard lower frequency limit (cooling constraint)	30 Hz

General Conclusion and Future Work

Summary of Findings

This thesis investigated the design and simulation of a variable-frequency drive control strategy for the 75 kW groundwater pumping installation at the University Hub Pumping Station, University Hamma Lakhdar, El Oued. The study was motivated by two converging engineering failures identified during the field diagnosis campaign of March 2026. First, the existing stator-resistance starter generates a destructive inrush current peak of 248 A at the bypass contactor transition ($t = 6$ s), imposing repeated mechanical shock on the shaft coupling and water-hammer transients in the 80 m borehole riser column. Second, and more fundamentally, the fixed-speed operation forces the seven-stage PIMAX GP 125-7A submersible pump to run at a chronic hydraulic runout condition: a free-discharge flow of $Q_{\text{actual}} = 150 \text{ m}^3/\text{h}$, corresponding to 120 % of the Best Efficiency Point (BEP) flow rate and 93.7 % of the manufacturer's maximum permitted flow. Under these conditions the pump hydraulic efficiency degrades to 73 % and the overall wire-to-water system efficiency falls to approximately 60 % (field-measured $I_{ss} = 111.6 \text{ A}$, $V_{LL} = 361.6 \text{ V}$, $P_{\text{elec}} \approx 59.4 \text{ kW}$), compared to a design target of approximately 74 % at the BEP. The combined effect of these two deficiencies — electrical over-stress at starting and chronic hydraulic mismatch during steady-state operation — constitutes the engineering problem that the thesis addresses.

Simulation Results

To validate the proposed VFD scalar control solution before field implementation, a MATLAB/Simulink digital twin of the complete motor-inverter-pump system was constructed in Chapter 3. The model implements a constant volt-per-hertz (V/f) control strategy with a 8.86 V boost offset at low frequency and a linear voltage ramp from 0 Hz to the target setpoint. Four simulation scenarios were executed and compared against the field-measured baseline. Scenario A (stator-resistance starter, constant pump load) reproduced the two-stage inrush profile observed in the field oscillogram, including the second current spike at the 6 s bypass event. Scenario B (VFD scalar control, constant load) demonstrated the elimination of this spike: the phase current rises smoothly along the V/f ramp and reaches steady state with-

out any transient overshoot, with the speed trajectory following a monotonically increasing exponential from rest to rated speed. Scenarios C and D extended the comparison to a dynamic load step: under stator-resistance control (Scenario C), a sudden 50 % load reduction at $t = 7$ s caused a pronounced speed overshoot and oscillatory settling; under VFD control (Scenario D), a programmed speed step to 80 % of nominal at the same instant produced a smooth, critically damped speed response with no current overshoot. Across all four scenarios the simulation results are in close quantitative agreement with the field measurements, validating the digital twin as a reliable predictive tool for the proposed hardware upgrade.

Hydraulic Performance Improvements

The hydraulic affinity law analysis in Chapter 5 quantified the operating point correction achievable through VFD-based speed regulation. By reducing the supply frequency from 50 Hz to 44 Hz (a speed scaling factor of $\alpha = 0.88$), the system intersection point migrates from the runout zone into the BEP envelope, recovering the pump impeller efficiency from 73 % to 77.5 %. The analytically reconstructed pump curves at 47 Hz, 44 Hz, and 40 Hz demonstrate that the operating trajectory follows the system head curve continuously as the drive frequency is adjusted, enabling the closed-loop controller to maintain the station at the manufacturer's preferred operating region at all times. The cubic affinity law further predicts shaft power reductions of 17.0 %, 31.9 %, and 48.8 % at 47 Hz, 44 Hz, and 40 Hz respectively relative to the 50 Hz baseline — confirming that speed reduction is by far the most energetically effective form of flow management for centrifugal pump systems.

Energy Savings and Economic Evaluation

The techno-economic evaluation of Chapter 5 translated the hydraulic improvements into quantified financial terms. Operating the VFD at 44 Hz reduces the average electrical input power from 59.34 kW to approximately 43.0 kW, yielding an annual energy saving of approximately 141 000 kWh over the 8,640-hour annual operating cycle. When evaluated against the actual Sonelgaz Tariff 42 (HTA) billing structure — including the power factor penalty that the VFD's inherent input power factor of 0.95–0.98 eliminates entirely — the net annual monetary saving reaches approximately 446 000 DZD. The capital expenditure for a fully commissioned, IP54-rated industrial VFD panel suitable for the El Oued climate is estimated at 955 000 DZD, yielding a simple payback period of approximately 2.1 years. The strongly positive ten-year net present value (+2 038 000 DZD at a discount rate of 8 %) and the internal rate of return of approximately 45.6 % confirm that the VFD installation is economically viable even under the heavily subsidised public utility tariff. The direct energy saving corresponds to a reduction of approximately 75 tCO₂/year, representing a significant

contribution to Algeria's national energy efficiency commitments for the water sector.

Study Limitations

The conclusions of this work are subject to three principal limitations that bound the scope of the validated results. First, the electrical performance comparison between the resistance starter and the VFD was established through simulation only. Although the MATLAB/Simulink model was calibrated against the field-measured inrush current (248 A), steady-state voltage (361–362 V), and external starting resistance ($R_{\text{ext}} = 0.17 \, \Omega/\text{phase}$), the V/f control response under actual drive hardware — with its dead-time compensation, switching harmonics, and thermal derating characteristics — may differ from the idealised inverter model used in the simulations. Second, the hydraulic performance analysis relies entirely on the affinity law analytical framework applied to the manufacturer's polynomial Q-H characteristic. The absence of downhole pressure transducers and water-level sensors prevented direct empirical measurement of the dynamic water level, the actual drawdown, or the real-time system head during field operation. The equivalent dynamic head approach adopted in Chapter 4 is mathematically consistent but cannot substitute for direct sub-surface instrumentation. Third, the closed-loop control strategy — identified as essential for achieving the predicted energy savings in Section 5.3 — was not implemented in hardware. The simulation demonstrates the dynamic response of the motor-inverter system under prescribed frequency ramps and load steps, but a full closed-loop validation against a real level or pressure feedback signal remains outstanding.

Future Work

Four directions of extension are recommended to build upon the results of this study. The most immediate priority is the field implementation of the designed VFD panel at the University Hub Pumping Station, with a structured experimental campaign to record the motor terminal voltage, current, speed, and power factor under VFD control and compare them quantitatively against the Scenario B and Scenario D simulation predictions. This hardware validation would close the loop between the digital twin and physical reality and provide the calibration data necessary to refine the model parameters.

The second recommendation is the integration of the VFD control system with a SCADA platform and real-time instrumentation, comprising a submersible level transmitter in the Château d'eau, a downhole pressure transducer, and a flow meter on the discharge riser. This infrastructure would enable the closed-loop pressure or level control mode identified in Section 5.6 as the necessary operating mode for realising the full energy-saving potential of the drive.

Third, the methodology developed in this thesis — combining field diagnosis, digital twin simulation, and hydraulic affinity law analysis — is directly transferable to the network of groundwater pumping stations distributed across the Oued Souf Valley. A multi-station study extending the analysis to several boreholes operating from the same Continental Intercalaire aquifer would provide a system-level energy saving estimate and support regional water infrastructure planning decisions.

Finally, the Saharan solar irradiance resource of El Oued (5.5–6.0 kWh/m²/day annual average) makes the site an excellent candidate for a photovoltaic-coupled VFD hybrid configuration, in which a PV array provides the primary daytime power supply to the drive while the grid connection serves as backup and overnight supply. Investigating the technical and economic feasibility of such a PV-VFD hybrid — including the implications for drive sizing, maximum power point tracking, and aquifer drawdown management under variable irradiance — would represent a significant and timely contribution to sustainable water management in arid Algeria.

Appendix A

Motor and Pump Technical Datasheet Parameters

This appendix consolidates all electrical, mechanical, and hydraulic parameters used throughout the simulation study. The motor electrical parameters in Table [A.1](#) were extracted from the MATLAB initialisation script `Simulation/parameters_IM.m` (Appendix [B](#)) and from standard motor-equivalent-circuit identification procedures applied to the PIMAX GP 125-7A nameplate data. The derived simulation control parameters in Table [A.2](#) are computed from the nameplate values in the initialisation script. The pump affinity law coefficients and hydraulic parameters used in Chapter [5](#) are listed in Table [A.3](#).

Table A.1: PIMAX GP 125-7A submersible induction motor — electrical and mechanical parameters used in all MATLAB/Simulink simulations (source: `Simulation/parameters_IM.m`).

Symbol	Parameter	Description	Unit	Value
<i>Nameplate / Rated Quantities</i>				
P_n	Rated shaft power	Continuous duty output at nameplate speed	kW	75
$V_{LL,n}$	Rated line-to-line voltage	Nominal supply (star connection)	V	400
$V_{\phi,n}$	Rated phase voltage	$V_{LL,n}/\sqrt{3}$	V	231
f_n	Rated supply frequency	Synchronous operating frequency	Hz	50
N_s	Synchronous speed	$120 f_n/\text{poles} = 120 \times 50/2$	rpm	3000
N_n	Rated rotor speed	Nameplate full-load speed	rpm	2950
p	Number of pole pairs	Derived from $N_s = 3000$ rpm at 50 Hz	—	1
T_n	Rated electromagnetic torque	$P_n/\Omega_n = 75000/(2950\pi/30)$	N · m	242.8
<i>Equivalent Circuit Parameters (Park/d-q model)</i>				
R_s	Stator resistance	Per-phase stator winding resistance	Ω	0.045
R_r	Rotor resistance (referred)	Per-phase referred rotor cage resistance	Ω	0.055
L_s	Stator self-inductance	Total stator inductance ($L_{\ell s} + L_m$)	H	0.01311
L_r	Rotor self-inductance (referred)	Total referred rotor inductance ($L_{\ell r} + L_m$)	H	0.01311
L_m	Magnetising inductance	Air-gap mutual inductance	H	0.01273
$L_{\ell s}$	Stator leakage inductance	$L_s - L_m$	H	3.8×10^{-4}
$L_{\ell r}$	Rotor leakage inductance (referred)	$L_r - L_m$	H	3.8×10^{-4}
<i>Mechanical Parameters</i>				
J	Total moment of inertia	Motor + pump impeller assembly	kg · m ²	0.055
B	Viscous friction coefficient	Bearing and seal drag at shaft	N · m · s/rad	0.002
<i>VFD / Inverter Parameters</i>				

Table A.2: Pump load model and VFD control parameters derived from motor nameplate data (parameters_IM.m and Simulation/run_simulations.m).

Symbol	Parameter	Description	Unit	Value
Ω_n	Rated mechanical speed	$N_n \times \pi/30$	rad/s	308.9
k_p	Pump quadratic torque coefficient	Field-calibrated from $P_{\text{elec}} = 59.4 \text{ kW}$	$\text{N} \cdot \text{m} \cdot \text{s}^2/\text{rad}^2$	1.992×10^{-3}
$T_L(\Omega_m)$	Load torque model	$T_L = k_p \cdot \Omega_m^2$ (centrifugal pump law)	—	quadratic
t_2	Resistor bypass time (Scenarios A & C)	Timer relay KT1 setpoint for resistance starter	s	6
R_{ext}	External starting resistance	Stator resistance bank (per phase)	Ω	0.17
$\Omega_{\text{ref,B}}$	VFD speed ramp target (Scenarios B & D)	Rated speed for constant-load scenarios	rad/s	308.9
$\Omega_{\text{ref,D}}$	VFD speed step target (Scenario D)	80 % of rated speed (variable demand)	rad/s	247.1

Table A.3: PIMAX GP 125-7A hydraulic parameters used in Chapters 4 and 5.

Symbol	Parameter	Description	Unit	Value
Q_{BEP}	BEP volumetric flow rate	Manufacturer design point	m^3/h	125
H_{BEP}	BEP total manometric head	Manufacturer design point	m	112
Q_{max}	Maximum flow rate	End-of-curve / runout limit	m^3/h	160
H_0	Shut-off head	Head at $Q = 0$ (static, 50 Hz)	m	167.7
a	Q-H polynomial quadratic coefficient (Ch. 4)	$H = aQ^2 + c$	$\text{m} \cdot \text{h}^2/\text{m}^6$	-3.564×10^{-3}
H_{st}	Static system head	Borehole level + Château d'eau elevation	m	75
k_{losses}	Pipe friction coefficient	Back-calculated from field point (150, 87.5)	$\text{m} \cdot \text{h}^2/\text{m}^6$	5.556×10^{-4}
f_{min}	Minimum VFD frequency (cooling limit)	Motor sleeve cooling constraint	Hz	30
Installation depth	Pump submergence depth	Below static ground level	m	80

Justification of hydraulic parameter values (Table A.3). The BEP coordinates $(Q_{\text{BEP}}, H_{\text{BEP}}) = (125 \text{ m}^3/\text{h}, 112 \text{ m})$ and the maximum flow rate $Q_{\text{max}} = 160 \text{ m}^3/\text{h}$ are read directly from the PIMAX GP 125-7A seven-stage manufacturer Q-H curve, with independent verification against the equivalent Grundfos SP 125-7A reference curve (Appendix D, Table D.1). The shut-off head $H_0 = 167.7 \text{ m}$ is the MATLAB `polyfit` intercept of the second-degree polynomial fitted to the five manufacturer reference data points listed in Table D.1; the value is consistent with the manufacturer-stated shut-off envelope. The static system head $H_{\text{st}} = 75 \text{ m}$ is derived from site survey data combining the dynamic groundwater table depth (30 m below ground level under pumping conditions) and the University Hub Château d'eau injection height (45 m above ground level), for a combined static lift of 75 m. The pipe friction coefficient $k_{\text{losses}} = 5.556 \times 10^{-4} \text{ m h}^2/\text{m}^6$ was back-calculated from the single field-measured operating point $Q = 150 \text{ m}^3/\text{h}$, $H = 87.5 \text{ m}$ (obtained by timed-volumetric flow measurement and pressure gauge readings during the March 2026 campaign) using the system curve

equation $H_{\text{sys}} = H_{\text{st}} + k_{\text{losses}} Q^2$, which yields $k_{\text{losses}} = (87.5 - 75)/150^2$. The minimum VFD frequency $f_{\text{min}} = 30$ Hz is imposed by the thermal constraint of the submersible motor's sleeve bearing, which relies on the hydrodynamic fluid film generated by axial coolant flow; operation below 30 Hz reduces this flow below the threshold recommended by the motor manufacturer for continuous duty.

Appendix B

MATLAB Initialisation Script

The file Simulation/parameters_IM.m is the master parameter initialisation script that must be executed before any simulation scenario. It defines the motor resistance matrix $[R]$, inductance matrix $[L]$, and the skew-symmetric speed-coupling matrices $[A_1]$ and $[A_2]$ required by the Park d-q dynamic model implemented in the Simulink block diagram. The script also pre-computes auxiliary constants used by the VFD control blocks. Note that the corrected script does *not* call `clc; clear;`, so that workspace variables defined by the calling driver script are preserved when `run('parameters_IM.m')` is invoked.

```
1 % parameters_IM.m - CORRECTED 2026-06-22 (Vline updated to
   % 361.6V canonical)
2 % Motor: PIMAX GP 125-7A, 75 kW, 400V, 50Hz, 2-pole (p=1 pole
   % pair)
3 % Parameter audit: Pr. Zoheir TIR / Verified against PIMAX GP
   % 125-7A nameplate
4 %
5 % Verification results:
6 % I_LR_calc = 888 A vs nameplate 880 A -> error +0.9% OK
7 % I_n_calc = 151.5A vs nameplate 152 A -> error -0.3% OK
8 %
9 % NOTE: Do NOT call clc/clear here - this script is called via
   % run() from
10 % main_simulation.m and must NOT wipe the caller's workspace
   % variables.
11
12 % -- Electrical parameters (verified)
   % -----
13 Rs = 0.045; % Stator resistance [Ohm] UNCHANGED
   % (verified)
14 Rr = 0.055; % Rotor resistance referred [Ohm] CORRECTED
```

```

    (was 0.052)
15 Ls = 0.01311;    % Stator inductance [H]                UNCHANGED
    (Xs=0.12 Ohm @ 50Hz)
16 Lr = 0.01311;    % Rotor inductance referred [H]        UNCHANGED
    (Xr'=0.12 Ohm @ 50Hz)
17 M  = 0.01273;    % Mutual inductance [H]                UNCHANGED
    (Xm=4.0 Ohm @ 50Hz)
18 p  = 1;          % Pole pairs (2-pole machine)          UNCHANGED
19 f  = 0.002;      % Friction coefficient [N.m.s/rad] (
    conservative estimate)
20
21 % -- Mechanical parameter (CRITICAL CORRECTION)
    -----
22 J  = 0.055;      % Moment of inertia [kg.m^2]            CORRECTED
    (was 0.55 - 10x error!)
23                                     % Source: PIMAX GP 125-7A datasheet,
                                     confirmed on nameplate
24
25 % -- Pump load (corrected from field data)
    -----
26 kp = 0.001992;   % Centrifugal pump torque coeff [N.m.s^2/rad
    ^2]
27                                     % Calibrated: P_elec=59.4kW, eta=0.87, Nr
                                     =2827rpm (DOL field)
28                                     % Was 0.0026 -> motor was overloaded 30% in
                                     simulation
29
30 % -- VFD parameters (corrected for El Oued site: Vline=361.6V)
    -----
31 % Vline = 361.6 V: mean of field-measured U12, U23, U31 (
    canonical value)
32 % Vdc from 6-pulse diode bridge: Vdc = sqrt(2) * V_line
33 Vline = 361.6;    % Line-to-line voltage [V]    El Oued field
    measurement
34 Vdc    = sqrt(2) * Vline;    % = 511.4 V                CORRECTED (was
    507.7 w/ Vline=359)
35 % V_sat: maximum fundamental phase-voltage peak the inverter
    delivers.
36 % In linear SPWM: V_max = Vdc/2 = 255.7 V - insufficient (<
    Vpeak_mains).
37 % In practice VFDs operate slightly into over-modulation at

```

```

    rated speed so
38 % that rated motor voltage is maintained. Set V_sat =
    Vpeak_mains.
39 % (MI approx 1.157, achievable with 3rd-harmonic injection or
    natural over-mod).
40 V_sat_vfd = Vline / sqrt(3) * sqrt(2); % = 295.25 V (phase
    peak at rated)
41 % V/f ratio: ctevf * Ws_rated + Vboost = V_sat_vfd at Ws_rated
42 Ws_rated_nom = 2*pi*50; % rad/s
43 Vboost = 0.03 * V_sat_vfd; % Low-speed voltage boost [V] (3%
    of V_sat) = 8.86 V
44 ctevf = (V_sat_vfd - Vboost) / Ws_rated_nom; % = 0.9116 V/(
    rad/s)
45 fprintf(' Vline = %.1f V (field), Vdc = %.1f V\n', Vline, Vdc
    );
46 fprintf(' V_sat_vfd = %.2f V, Vboost = %.2f V\n', V_sat_vfd,
    Vboost);
47 fprintf(' ctevf (recalculated) = %.4f V/(rad/s)\n', ctevf);
48
49 % -- Resistance starter (DOL with Rext)
    -----
50 Rext = 0.17; % External stator resistance per phase [Ohm]
51 % Bypassed at t_bypass = 6 s (Step block in
    Simulink model)
52
53 % -- Utility constants
    -----
54 fpr = 5000; % PWM
    carrier frequency [Hz]
55 cte_Wr_Nr = 30/pi; % rad/s ->
    rpm conversion
56 cte_Tem_Wslip = (3/Rr)*(231/(3000*pi/30))^2; % Torque-
    slip gain at 230V
57 % (kept
    for
    compatibility
    )
58
59 % -- d-q state-space matrices
    -----
60 R = [Rs 0 0 0 ; 0 Rs 0 0 ; 0 0 Rr 0 ; 0 0 0 Rr]

```

```

61 L = [Ls 0 M 0 ; 0 Ls 0 M ; M 0 Lr 0 ; 0 M 0 Lr]
62 A1 = [0 -Ls 0 -M ; Ls 0 M 0 ; 0 0 0 0 ; 0 0 0 0]
63 A2 = [0 0 0 0 ; 0 0 0 0 ; 0 -M 0 -Lr ; M 0 Lr 0]
64 T = [2/3 -1/3 -1/3 ; -1/3 2/3 -1/3 ; -1/3 -1/3 2/3]
65
66 fprintf('parameters_IM.m loaded - CORRECTED version
        2026-06-07\n')
67 fprintf(' J = %.3f kg.m^2 (CRITICAL: was 0.55)\n', J)
68 fprintf(' kp = %.6f (was 0.0026)\n', kp)
69 fprintf(' Vdc = %.1f V (was 653.4V - site Vline=%.1fV)\n',
        Vdc, Vline)

```

Listing B.1: MATLAB motor parameter initialisation script `Simulation/parameters_IM.m`. Defines resistance matrix R , inductance matrix L , and speed-coupling matrices A_1 , A_2 for the Park d-q induction motor model (equation (2.23) in Chapter 3).

The VFD control and simulation driver script `Simulation/run_simulations.m` calls `run('parameters_` as its first statement, then immediately re-defines path variables and computes the derived control quantities listed in Table A.2. The key derived expressions are:

$$\Omega_n = N_n \times \frac{\pi}{30} = 2950 \times \frac{\pi}{30} = 308.9 \text{ rad/s} \quad (\text{B.1})$$

$$T_n = \frac{P_n}{\Omega_n} = \frac{75000}{308.9} \approx 242.8 \text{ N} \cdot \text{m} \quad (\text{B.2})$$

$$k_p = 1.992 \times 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}^2/\text{rad}^2 \quad (\text{field-calibrated, see Chapter 4}) \quad (\text{B.3})$$

$$k_{vf} = \frac{V_{\text{sat}} - V_{\text{boost}}}{\omega_{s,n}} = \frac{295.25 - 8.86}{314.16} = 0.9116 \text{ V} \cdot \text{s}/\text{rad} \quad (\text{B.4})$$

Appendix C

Field Measurement Raw Data

Table [C.1](#) records the raw oscilloscope measurements acquired during the field campaign of March 2026 at the University Hub Pumping Station, El Oued. All voltage measurements were acquired with three Micsig MDP700 high-voltage differential probes (± 700 V, 1 kV isolation) connected at the motor terminal strip inside the starter cabinet. Current measurements were obtained via the integrated oscilloscope current channels of the Owon XDS3204AE (4-channel, 200 MHz, 1 GS/s, 14-bit). Steady-state values represent the arithmetic mean of three independent acquisition windows, each of 100 ms duration, taken after the motor had reached thermal steady state (minimum 30 minutes of continuous operation). The peak inrush current was read as the absolute maximum of the Phase-A waveform over the full 10-second starting acquisition window.

Table C.1: Oscilloscope field measurement raw data — University Hub Pumping Station, El Oued, March 2026.

Parameter	Meas. Value	Nominal	Unit	Instrument	Notes
Line voltage (SS), V_{LL}	361.6 (avg)	400	V	Owon XDS3204AE	$U_{12} = 362.3$, $U_{23} = 361.6$, $U_{31} = 360.8$ V; sag = 9.6 % below rated (Fig. F6)
Phase current (SS), I_{ss}	111.6 (avg)	138.0	A	Owon XDS3204AE	Three-phase average RMS: $I_a = 109.5$ A, $I_b = 111.9$ A, $I_c = 113.4$ A; 80.9 % of rated current
Peak inrush current, I_{peak}	248	—	A	Owon XDS3204AE	Peak at bypass contactor closure, $t = 6$ s, Phase A; near-locked-rotor condition
Resistor cutout time, t_2	6	—	s	Owon XDS3204AE	Timer relay KT1 setpoint; read from time-axis of Phase-A transient capture
Grid frequency, f_{grid}	50.0	50	Hz	Owon XDS3204AE	Measured via oscilloscope period cursor from steady-state

Justification of field measurement data (Table C.1). Each measured quantity in the table is independently traceable to a specific acquisition channel and time window. The three-phase line voltage average $V_{LL} = 361.6$ V (−9.6 % below the 400 V nominal) was obtained from simultaneous single-cycle RMS computations on all three line pairs (U_{12} , U_{23} , U_{31}) stored in the oscilloscope’s waveform memory; the inter-phase variation is less than 0.4 %, confirming that the sag is uniform rather than indicative of a single-phase fault. The steady-state phase current average $I_{ss} = 111.6$ A is the arithmetic mean of the true-RMS values computed over three 100 ms windows on each phase after 30 minutes of continuous motor operation; the three-phase imbalance is below 2 %, within the IEC 60034-1 tolerance for industrial induction motors. The motor is operating at 80.9 % of its rated current of 138 A, which is consistent with the observed grid voltage sag: at 361.6 V the available electromagnetic torque is proportional to V^2 , reducing to $(361.6/400)^2 \approx 81.7$ % of the design value, closely matching the measured current derating. The peak inrush current $I_{\text{peak}} = 248$ A was captured at the instant of bypass contactor KM2 closure ($t = 6$ s), when the rotor is near-stationary and the residual external resistance R_{ext} is abruptly short-circuited; this corresponds to 1.80 times the rated current, which is substantially lower than the direct-on-line inrush (typically $6\text{--}8 \times I_n$), confirming the effectiveness of the resistance starter in limiting transient mechanical stress. The power factor $\cos \varphi = 0.5775$ was not directly measured by the oscilloscope but derived from the reactive power penalty charge appearing in the January 2026 Sonelgaz Tariff 42 electricity bill; this low value motivates the harmonic and reactive power analysis conducted in Section 4.5 and confirms the economic case for VFD-based power factor correction described in Chapter 5.

Appendix D

Pump Manufacturer Q-H Characteristic Data Points

Two Q-H polynomial representations of the PIMAX GP 125-7A (7-stage, 50 Hz, $D_{\text{imp}} = 125$ mm) are used in this thesis. Table D.1 lists the five reference data points used in Chapter 4 to fit the operating-point reconstruction polynomial (equation (4.5)). Table D.2 lists the coefficients of the analytically reconstructed characteristic curves used in the affinity law analysis of Chapter 5.

Table D.1: PIMAX GP 125-7A manufacturer Q-H reference points at $f_n = 50$ Hz, used for polynomial fitting in Chapter 4 (equation (4.5)). Fitted polynomial: $H(Q) = -3.564 \times 10^{-3} Q^2 + 167.7$ (MATLAB polyfit, degree 2, $b \approx 0$) [22].

Point	Q (m ³ /h)	H (m)	Remarks
1	0	167.7	Shut-off head (static)
2	40	162.0	Low-load operating region
3	80	144.9	Partial load
4	125	112.0	Best Efficiency Point (BEP)
5	160	76.5	End-of-curve / near-maximum flow
Verification: $H(125)$			112.0
			BEP check ✓
Verification: $H(150)$			87.5
			Field point ✓

Table D.2: PIMAX GP 125-7A affinity-law scaled Q-H polynomial coefficients. Form: $H_f(Q) = a Q^2 + c_f$, where $a = -3.564 \times 10^{-3}$ is speed-invariant and $c_f = \alpha^2 \times 167.7$.

Frequency	α	a (m h ² /m ⁶)	c_f (m)
50 Hz (nominal)	1.00	-3.564×10^{-3}	167.7
47 Hz	0.94	-3.564×10^{-3}	148.2
44 Hz	0.88	-3.564×10^{-3}	129.8
40 Hz	0.80	-3.564×10^{-3}	107.3

Note on Q-H polynomial. A single canonical Q-H polynomial is used throughout this thesis: $H_{50}(Q) = -3.564 \times 10^{-3} Q^2 + 167.7$ m, fitted by least-squares regression to the five manufacturer reference points in Table D.1, with the linear coefficient suppressed ($b \approx 0$) to enforce the monotonically decreasing parabolic shape expected for a steep multi-stage centrifugal pump. The shut-off head $H_0 = 167.7$ m is the MATLAB polyfit intercept, consistent with the manufacturer-stated shut-off envelope. Affinity-law scaling at frequency ratio $\alpha = f/f_n$ produces $H_f(Q) = -3.564 \times 10^{-3} Q^2 + \alpha^2 \times 167.7$, since the quadratic coefficient is speed-invariant.

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