International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 37 العدد
Part 1 المجلد

http://www.doi.org/10.62341/asam0952

Received	2025/08/28	تم استلام الورقة العلمية في
Accepted	2025/09/24	تم قبول الورقة العلمية في
Published	2025/09/52	تم نشر الورقة العلمية في

Comparative Analysis of Induction Motor Starting Methods for Water Pumping Systems in Jado-Libya

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Abstract

This paper presents a comparative analysis of three induction motor starting methods—Direct-On-Line (DOL), Soft Starter, and Star-Delta—applied to a water pumping system in Jado, Libya. The system has experienced operational challenges, including high inrush currents, voltage dips, and frequent equipment failures. Simulation models were developed using NEPLAN software to evaluate the dynamic performance of each starting technique, focusing on starting current, and voltage stability. Load flow analysis and optimal pump separation configurations were also investigated. The results demonstrate that while DOL is cost-effective, it causes significant voltage drops, whereas Star-Delta reduces inrush current but introduces transient disturbances. The Soft Starter emerged as the most efficient solution, offering smooth acceleration and minimal electrical stress. Practical recommendations are provided to enhance system reliability and reduce maintenance costs.

Keywords: Induction motors, motor starting methods, DOL, Soft Starter, Star-Delta, voltage stability, NEPLAN simulation.

http://www.doi.org/10.62341/asam0952

تحليل مقارنة لطرق تشغيل المحركات الحثية لأنظمة ضخ المياه في جادو – ليبيا

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الملخص

تقدم هذه الورقة تحليلاً مقارناً لثلاث طرق لبدء تشغيل المحركات الحثية – المباشرة على الخط (DOL)، وبادئ التشغيل الناعم، ونجمة دلتا، طبقت هذه النظريات الثلاث على نظام ضخ مياه في جادو، ليبيا. واجه النظام تحديات تشغيلية، شملت تيارات اندفاع عالية، وانخفاضات في الجهد، طُوّرت نماذج محاكاة باستخدام برنامج NEPLAN لتقييم الأداء الديناميكي لكل طريقة بدء، مع التركيز على تيار البدء، واستقرار الجهد. كما تم البحث في تحليل تدفق الحمل وتكوينات فصل المضخات المثلى. تُظهر النتائج أنه على الرغم من فعالية DOL من حيث التكلفة، إلا أنها تُسبب انخفاضات كبيرة في الجهد، بينما تُقلل Star–Delta من تيار الاندفاع ولكنها تُسبب اضطرابات مؤقتة. برز بادئ التشغيل الناعم كأكثر الحلول كفاءة، حيث يوفر تسارعًا سلسًا وجهدًا كهربائيًا ضئيلًا. وتُقدّم توصيات عملية لتعزيز موثوقية النظام وخفض تكاليف الصيانة.

الكلمات المفتاحية: المحركات الحثية، طرق بدء تشغيل المحركات، DOL، بادئ التشغيل الناعم، نجمة دلتا، استقرار الجهد، محاكاة NEPLAN.

1. Introduction

Electric motors play a vital role in both industrial and municipal water pumping systems by converting electrical energy into mechanical motion to drive pumps. Among the various types, three-phase squirrel cage induction motors are the most widely used because of their robustness, low maintenance requirements, and high efficiency [1]. Despite these advantages, motor starting continues to pose significant challenges. High inrush currents—typically 6 to 8 times the rated current—along with the associated voltage dips can degrade power quality, place stress on the grid, and potentially damage equipment [2].

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To mitigate these challenges, several starting methods have been developed. The Direct-On-Line (DOL) method is the simplest and least expensive approach; however, it imposes high electrical and mechanical stresses due to the large inrush current. The Star-Delta (Y-Δ) method partially alleviates this problem by reducing the starting current by about two-thirds, but it introduces transient disturbances during the switching transition from star to delta. In contrast, a soft starter provides a more advanced solution, using thyristor-based control to gradually ramp up the applied voltage. This approach significantly reduces inrush current and mechanical stress, offering smoother acceleration and improved operational reliability [3].
Despite the availability of these solutions, many water pumping systems, particularly in developing regions, still rely on inefficient starting methods due to legacy infrastructure and cost constraints. This underscores the importance of evaluating different motor starting strategies in practical contexts.
The study focuses on the Jado water pumping system in Libya, which relies on 11 wells equipped with 55 kW motors, supplemented by 19 kW of auxiliary loads per site. Power is supplied from an 11 kV medium-voltage feeder linked to a remote substation.
To enhance system reliability and maintain acceptable voltage profiles, a dual-radial open-loop ring configuration has been proposed. This configuration enables load sharing between feeders while providing alternate supply paths during faults or maintenance. By using the NEPLAN simulation software, this study evaluates the performance of three motor starting techniques—DOL, Star-Delta, and Soft Starter—by conducting load flow analysis, assessing motor starting transients, and examining performance metrics such as starting current, torque characteristics, and voltage drop during acceleration. The goal is to determine the most suitable starting method for the Jado water pumping network, ensuring both technical efficiency and long-term reliability.
Finally, a review of existing literature confirms the relevance of this analysis. Previous studies highlight the drawbacks of DOL starting in weak networks, the transient challenges of Star-Delta switching, and the growing adoption of soft starters for smooth motor acceleration [3],[4]. These insights provide a foundation for the comparative analysis presented in this paper.

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2. Methodology

The methodology is structured around detailed model development, simulation studies, and performance evaluation of the Jado pumping network as shown in figure (1). Both steady-state load flow and dynamic starting simulations were conducted using the NEPLAN power system analysis software.

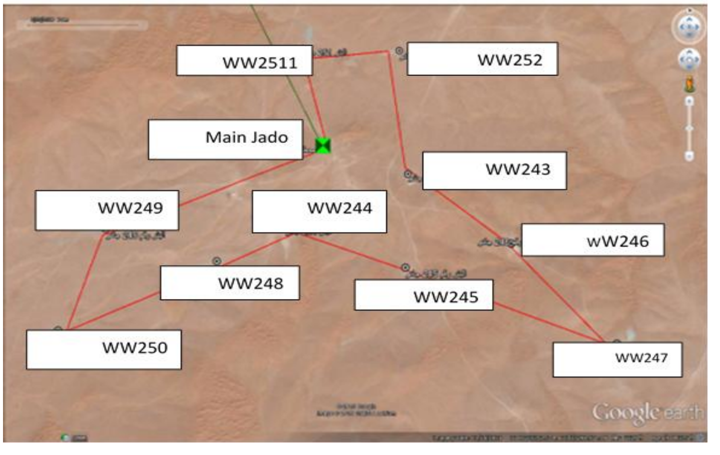

Fig.1: Water well field location [5]

A. Model Development

1. Network Topology: The actual geographic layout of the wells, feeder routes, and substation connections was replicated in the simulation model. The proposed dual-radial open-loop ring configuration was included with appropriate feeder impedances and switchgear representation.

2. Load Data: Each well site was modeled with two load components:

- Motor load: 55 kW induction motor modeled with detailed parameters, including rated voltage, efficiency, power factor, and starting characteristics.

- Auxiliary load: 19 kW static demand representing site services such as lighting, chlorine dosing, and air-conditioning.

3. Source Parameters: The substation's short-circuit capacity, transformer ratings, and feeder impedances were incorporated to accurately represent the supply system.

B. Simulation Studies

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Three categories of simulations were carried out:
1. Load Flow Analysis: Evaluated system voltage stability and voltage drop under peak loading. The results were benchmarked against international voltage tolerance standards, which require ≥ 80% at motor terminals during starting (NEMA MG-1, IEC 60034-12) and ≥ 85–90% across the network under normal operation (IEEE Std 141) [4]–[6].

2. Motor Starting Analysis: Dynamic simulations were conducted for three starting methods—DOL, Star-Delta, and Soft Starter. Evaluation metrics included:

- Starting current magnitude (multiple of full-load current),
- Acceleration time to rated speed,
- Transient voltage dip at motor terminals and the remote substation bus.

C. Assumptions and Constraints
To ensure clarity and consistency, several assumptions were made:
- The number of motors that can be started simultaneously is determined by ensuring that the terminal voltage during startup remains greater than or equal to 80% of the rated voltage.
- Ambient conditions and motor load torque characteristics were considered uniform across all sites.
- Protective device operation and relay coordination were excluded from this study but accounted for in broader planning processes.

By following this structured approach, the study provides a robust comparative framework for evaluating motor starting methods in terms of voltage stability, reliability, and compliance with international standards, thus directly addressing the challenges outlined in the introduction.

3. **Results and discussion.**

3.1 Load Flow Study and Optimal Feeder Separation

A load flow analysis was conducted using NEPLAN to assess voltage levels and line loading under peak operating conditions. Initial results showed undervoltage at several nodes, breaching the -5% nominal limit specified by IEC 60038. Figure (2) illustrates the results of the load flow study.

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To maintain the voltages within a permissible limit, one Mega Var shunt capacitor bank was installed at the 11 kV busbar of the main pumping station to keep the voltage within permissible limits, the results are shown in fig. (3). This provided local reactive power support, significantly improving voltage stability.

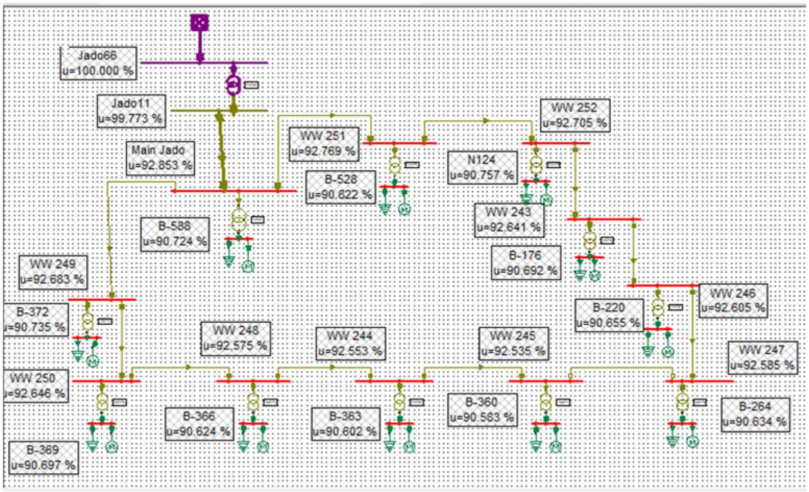

Fig.2: Load flow results before adding the capacitor

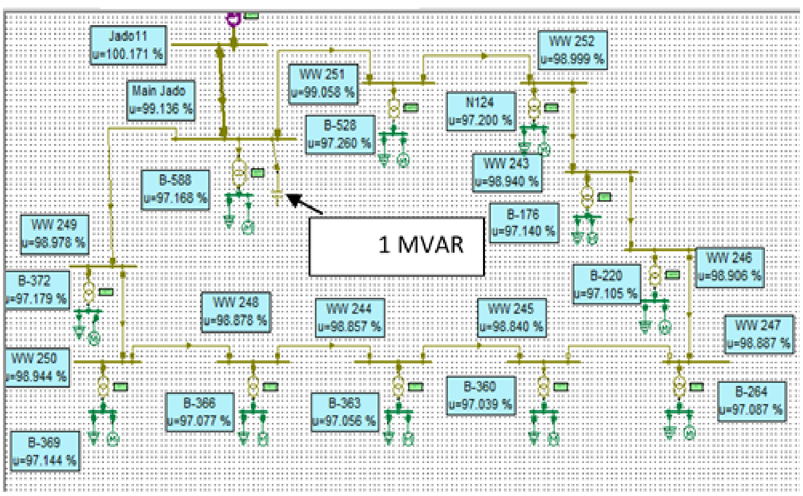

Fig.3: Load flow results after adding the capacitor bank.

3.2 Motor Starting Analysis

The study of motor starting represents a critical aspect in the design and analysis of electrical power systems, particularly when dealing with large loads or operating within power-limited networks. The primary objective of such a study is to ensure that the power system is capable of handling the high inrush current associated with motor

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startup, without causing negative impacts on voltage stability or the performance of other connected loads.

The most important technical criteria typically adopted when evaluating system performance during motor starting:

✓ Voltage Drop Criterion

Controlling voltage drop during motor startup is among the most significant factors affecting system stability. The high inrush current should not cause excessive voltage sag, either at the motor terminals or at other points in the network.

- At the motor terminals: Voltage should not fall below 80% of the nominal value.[5],[7]

- In the rest of the network: Voltage should preferably remain above 85%, and in some regulatory environments, above 90% of the nominal value.[6]

✓ Starting Time Criterion

The motor must reach its rated speed within an acceptable time frame from both thermal and mechanical perspectives, to prevent the exceedance of thermal limits.

- Standard motors: Typically require less than 10 seconds to start.[2]

- Special cases (e.g., large motors or those using soft starters): Startup time may extend to 15–20 seconds, depending on manufacturer specifications.[2]

✓ Thermal Limit Criterion

The startup process must not cause the winding temperature to exceed the allowable thermal limits, in order to avoid insulation degradation or future electrical failures. Thermal withstand curves provided by manufacturers are used for verification.

✓ Inrush Current Criterion

Motor starting typically requires a high initial current, usually between 5 to 7 times the rated current. The system components—such as circuit breakers and cables—must be able to withstand this current without damage or unwanted tripping.

Simulations were carried out to evaluate the network's behavior during motor startups using three methods: Direct-On-Line (DOL), Soft Starter, and Y-Delta. Several startup scenarios were tested, including single and multiple motor operations.

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3.2.1 Direct-On-Line (DOL) Starting

Case 1: Analysis of Simultaneous Starting of Motor WW247

The DOL method connects motors directly to the line without voltage reduction. When Motor WW247 was started, voltage dropped by approximately 15.7%. The voltage and current behavior during startup of motor WW247 is shown in figures (4) and (5) These results demonstrate that the DOL method, although simple and low-cost, poses significant risks of voltage instability and equipment stress under grouped motor starting conditions.

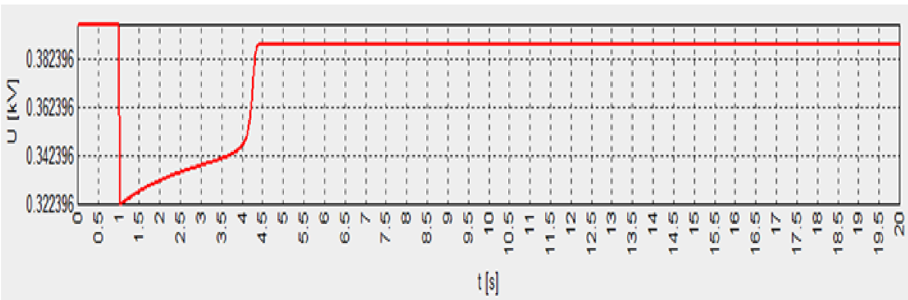

Fig. 4: Voltage behavior of motor WW24

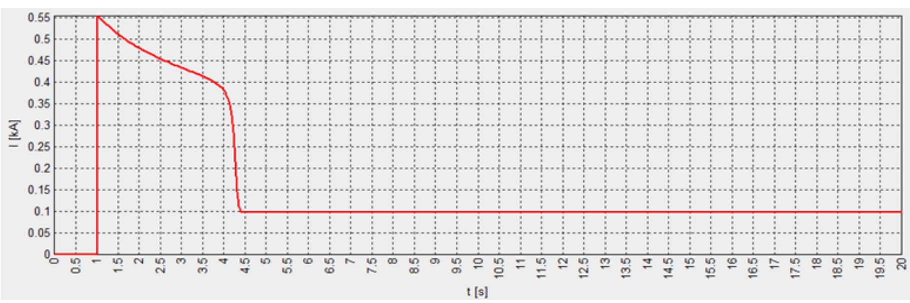

Fig.5: Current behavior of motor WW247

From the figures (4) and (5):

1. Voltage Variation at Motor WW247 (U – Motor247):

- The motor is energized at t = 1 second, causing an instantaneous voltage dip from approximately 0.382 kV to around 0.322 kV.
- After the initial drop, the voltage begins to recover gradually and stabilizes around t ≈ 4.4 seconds, reaching its nominal value.
- This represents a voltage sag of nearly 60 V (~15.7%), which, while significant, remains within acceptable bounds if the system is designed to tolerate such events.

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- The post-recovery stabilization confirms the transition from the transient inrush period to steady-state operation.

2. Current response (I – Motor247):

- At startup (t = 1 s), the inrush current peaks at approximately 0.52 kA (520 A).
- The current then decreases smoothly as the motor accelerates, eventually settling at the rated current of about 100 A by t ≈ 4.4 seconds.
- This behavior aligns with theoretical expectations for an inrush current magnitude of 6× the rated current.
- The controlled reduction in current and its stabilization confirm that the system can accommodate the start-up load effectively without triggering protective devices.
- The motor's starting current was consistent with theoretical predictions and was successfully absorbed by the network.
- The voltage sag, although noticeable, did not drop below 0.32 kV, indicating that the network can withstand the worst-case single-motor start.
- It is recommended to proceed with caution when starting additional motors afterward, as cumulative effects may lead to unacceptable voltage drops or overloads.

Case 2: Analysis of Simultaneous Starting of Motors WW247 and WW246

In this scenario, two adjacent motors (WW247 and WW246) were started simultaneously to evaluate the cumulative effect on the system voltage and current response. The results shows that the voltage still within the limit.

Case 3: Analysis of Simultaneous Starting of Motors WW247, WW246, and WW243

This scenario simulates the concurrent start-up of three motors located on the same feeder path, increasing the electrical stress on the network. The voltage of motor WW247 is shown in figure (6).

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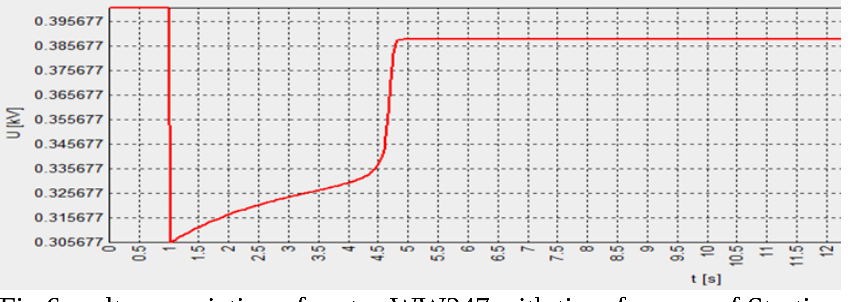

Fig.6: voltage variation of motor WW247 with time for case of Starting Motor WW247, WW246 and WW243

From the figure above:

- The voltage drops from ~0.385 kV to ~0.305 kV, indicating a sag of ~80 V, or approximately 20.8%.
- Voltage recovery begins after the inrush period and stabilizes by t ≈ 4.8 s, returning to nominal conditions.
- From the above, starting the three motors at the same time is not recommended, so it should startup only two motors at the same time and after 5 seconds the other motors will start.

Case 4 :Analysis of Starting of Motors WW247, WW246 Simultaneously at t = 1s ,WW243, WW252 Simultaneously at t = 6s and WW251 at t = 11s:

Startup Sequence

- t = 1s: Motors WW247 and WW246 start.
- t = 6s: Motors WW243 and WW252 start.
- t = 11s: Motor WW251 starts.

The voltages of motor WW247 and WW243 is shown in figures (7), (8) respectively

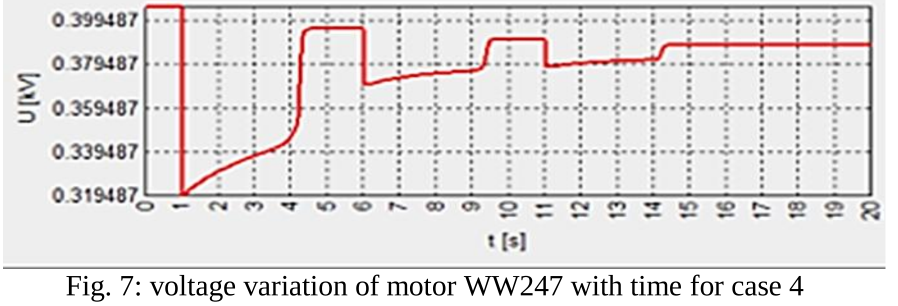

Fig. 7: voltage variation of motor WW247 with time for case 4

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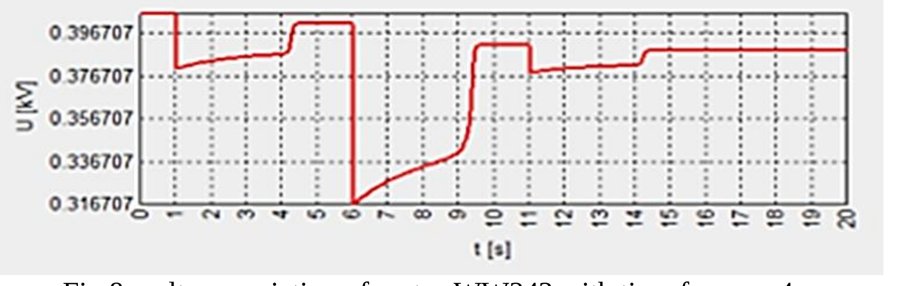

Fig.8: voltage variation of motor WW243 with time for case 4

From the figures above :

− Voltage Response (U – Motor247):

- At t = 1s: A voltage dip occurs immediately upon starting (due to inrush current from WW247 and WW246).
- From t = 1s to 4s: Voltage recovers gradually.
- At t = 6s: A second dip as WW243 and WW252 start.
- At t = 11s: A third, smaller dip due to WW251.
- After t = 12s: The voltage stabilizes and climbs toward the nominal value (~0.399 kV).

− Voltage Response (U – Motor243):

- At t = 1s: A small voltage fluctuation due to the startup of distant motors WW247 and WW246.
- At t = 6s: A deep dip due to local startup (Motor243 itself and WW252).
- At t = 11s: Another dip from WW251 startup.
- After t = 12s: Gradual recovery and stabilization around ~0.396 kV.
- Voltage dips are most severe when motors start locally.
- Motor243 experiences a deeper voltage sag at 6s because it is starting itself.
- Motor247, although affected by other motor startups, shows lesser voltage dips beyond its own startup.
- Simultaneous motor startups cause noticeable voltage dips.
- Motors located closer to each other (like 243 and 252) have greater mutual impact on voltage.

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- Staggered starts or soft starters could help mitigate voltage dips and improve system stability.

3.2.2 Soft Starter Method

Case 1: Analysis of Starting of Motor WW247 Using Soft Starter

This scenario involves the use of a Soft Starter to initiate the operation of Motor WW247. The soft starter gradually ramps up the voltage applied to the motor, which significantly reduces the starting current and mitigates voltage dips in the network. The voltage and current are shown in figures (9),(10) respectively.

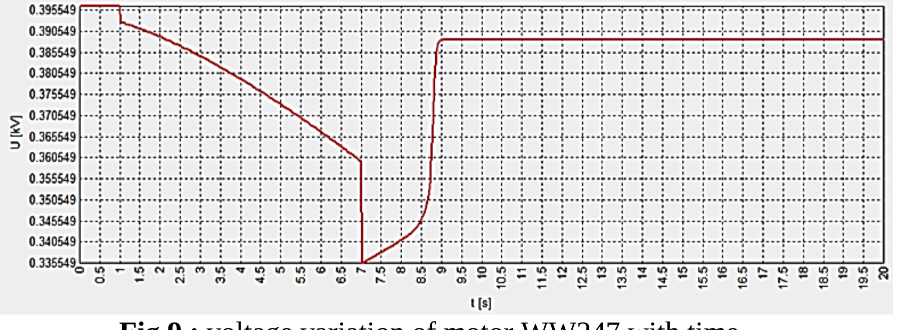

Fig.9 : voltage variation of motor WW247 with time

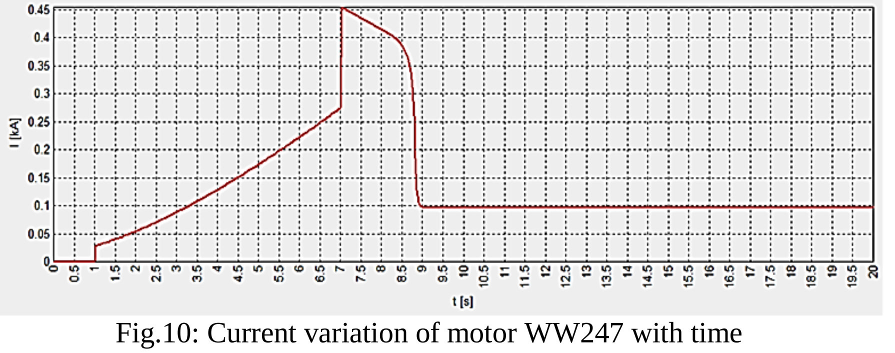

Fig.10: Current variation of motor WW247 with time

From the figures:

1. Voltage Response (U – Motor247):

- Initial voltage: ~0.395 kV
- Minimum voltage during ramp-up: ~0.335 kV
- Recovery and full voltage application occur at t ≈ 8.8 s, indicating a smooth startup transition.

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2. current Response (U – Motor247):

- The current begins from nearly zero, increasing linearly and smoothly with time.
- Maximum current during startup is ~0.4 kA, much lower than DOL startup (which reaches ~0.5 kA).
- Steady-state current is reached without any spikes or transients, around t ≈ 8.8 s.

The use of a soft starter for Motor WW247 has significantly improved startup performance. Voltage dip is well within acceptable limits, and the current profile is smooth and controlled, reducing stress on the electrical infrastructure.

Case 2: Analysis of starting of Motors WW247, WW246, WW243,
WW252 and WW251 Using Soft Starter

Two motors, three motors and four motors startup instantaneously are tested, and the voltage still in limiting range. Here five motors starting up instantaneously is tested and the results are shown in figure (11).

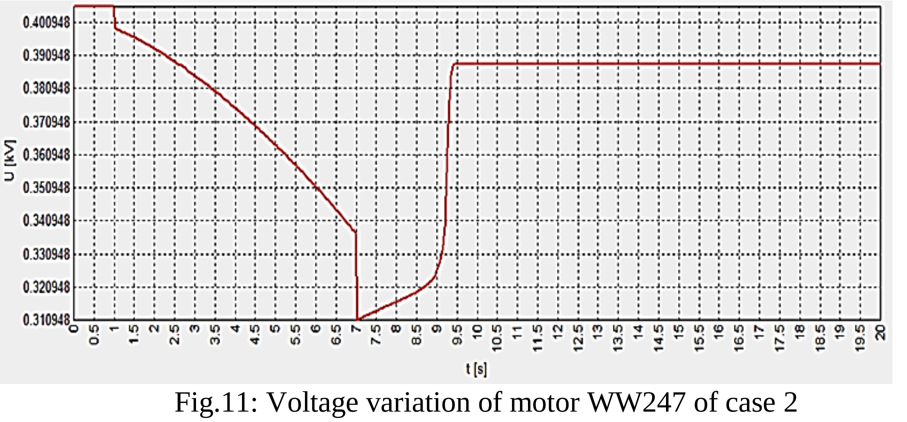

Fig.11: Voltage variation of motor WW247 of case 2

From the figures:

1. Voltage Response (U – Motor247):

- Initial Stage (0–1 s): The voltage is stable at approximately 0.405 kV, indicating normal conditions before motor starting.
- Gradual Voltage Drop Phase (1–7.0 s): A smooth, gradual voltage decrease is observed, reaching around 0.311 kV (81 % of motor voltage rating)

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This is a typical characteristic of soft starter operation, where voltage is ramped up slowly to reduce inrush currents.

- Recovery Phase (8–10 s): The voltage recovers quickly and stabilizes around 0.375–0.38 kV, close to the original pre-start condition but slightly lower due to the continuous load.

Soft starters enable gradual voltage ramp-up, reducing mechanical stress and inrush current. In this study, soft starters limited voltage dips and produced smooth current profiles, even with up to five motors starting sequentially.

3.2.3 Third scenario (Wye-Delta Transformer method)

Case 1: Analysis of starting of Motors WW247 Using Wye-Delta Starter

The Wye-Delta (Y-Δ) starting method is widely used to reduce the inrush current during the starting of induction motors. In this case, Motor WW247 was started using a Wye-Delta starter, and the voltage and current profiles were recorded and analyzed. The voltage and current are shown in figures (12),(13).

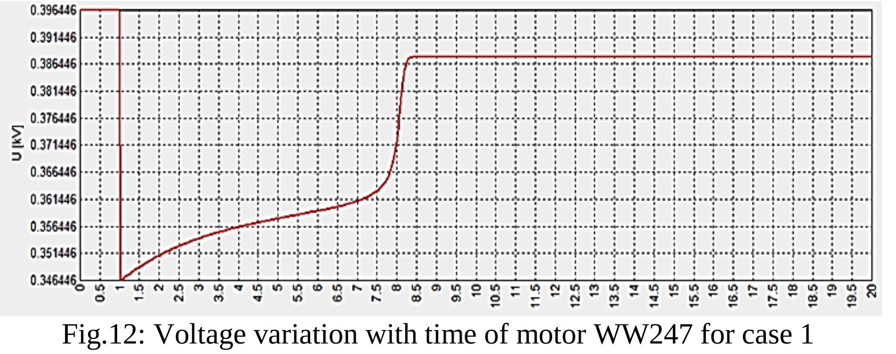

Fig.12: Voltage variation with time of motor WW247 for case 1

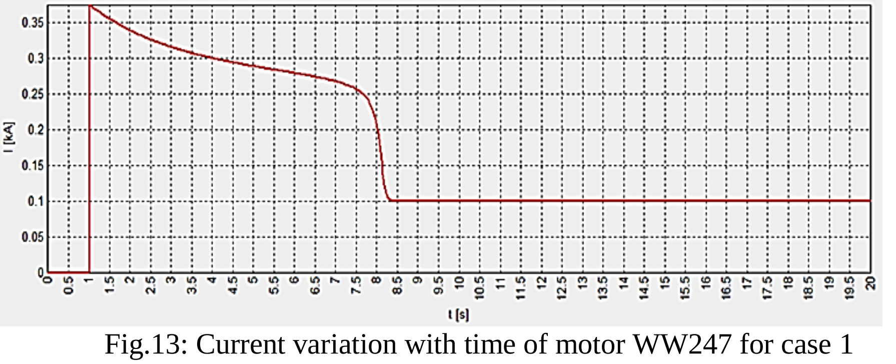

Fig.13: Current variation with time of motor WW247 for case 1

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From the figures:

1. Voltage Response (U – Motor247):

Upon starting, a noticeable drop in voltage was observed, consistent with the reduced line voltage applied during the Wye (star) connection phase. The voltage remained relatively stable during acceleration, followed by a sudden recovery at approximately 8.25 seconds when the transition to Delta connection occurred. This behavior is fully consistent with the expected pattern of Wye-Delta motor starting, where:

- Initial voltage drop occurs due to star connection (reduced phase voltage).
- Gradual stabilization as motor speed increases.
- Voltage recovery when switching to Delta connection, applying full line voltage to the motor.

2. Current Response (I – Motor247):

The current profile showed a moderate peak during initial starting (~0.3 kA), substantially lower than typical Direct-On-Line (DOL) starting currents. This initial peak is normal due to motor acceleration under reduced voltage. Following this, the current gradually decreased as the motor approached its ratedspeed. At the point of transition to Delta connection (~8.25 seconds), the current decreased sharply to a stable value (~0.1 kA), representing the normal operating current of Motor WW247.

The voltage and current behaviors observed during the Wye-Delta starting of Motor WW247 are entirely logical and in line with engineering expectations. The use of the Wye-Delta starter successfully:

- Limited the starting current.
- Reduced voltage stress on the network.
- Enabled a smooth transition to full-load operation without significant voltage disturbances.

Thus, the starting sequence of Motor WW247 using the Wye-Delta method can be considered successful and technically acceptable.

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Case 2: Analysis of starting of Motors WW247, WW246, WW243, WW252 and WW251 Using Wye-Delta transformer

The voltage behavior of motor WW247 is shown in figure (14).

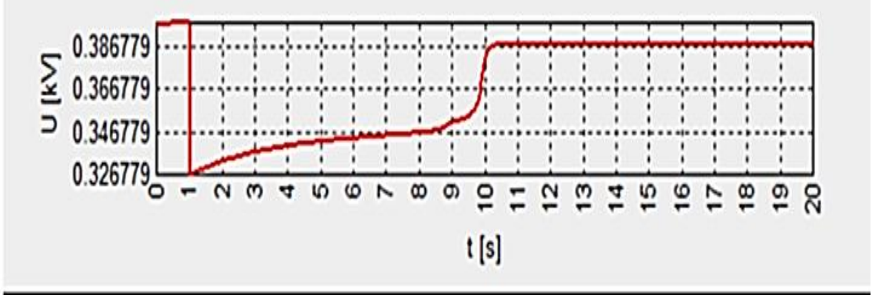

Fig.14: Voltage variation with time of motor WW247 for case 2

1. Voltage Response (U – Motor247):

- From 0s to 1s: Very sharp voltage dip expected during motor start (inrush current effect).
- From 1s to ~9s: Voltage slowly recovers but remains lower than nominal This is normal during Wye connection, where motors run at about 58% of line voltage.
- At ~9–10s: Sudden jump in voltage is observed ; this transition corresponds to switching from Wye to Delta, where the motor gets full line voltage.
- After 10s: Voltage stabilizes without oscillations. the motor starting using Wye-delta starter for Motors WW247, WW246, WW243, WW252, and WW251 is acceptable.

4- Conclusion

Motor starting presents significant operational challenges in water pumping systems, particularly in medium-capacity networks like the Jado pumping station. Our comprehensive study compared three starting methods through NEPLAN simulations, analyzing their impact on voltage stability, current behavior, and system reliability. The Direct-On-Line (DOL) method, while simple and economical, demonstrated substantial limitations. It generated inrush currents 6-8 times the rated current [2],[4] causing severe voltage drops that could compromise sensitive equipment. These findings align with IEEE standards [2] that recommend DOL only for small motors or robust networks with strong voltage support.

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Y-Delta starting showed improved performance, reducing starting current by up to 66% compared to DOL. However, the method introduced transient disturbances during the star-to-delta transition, consistent with observations by Chapman [8]. While economically attractive, these transients make it less suitable for high-inertia applications.

The Soft Starter emerged as the superior solution, demonstrating:

- Gradual voltage ramp-up via thyristor control.
- Minimal mechanical and electrical stress
- Excellent voltage stability during multiple motor starts
- Significant inrush current reduction

These advantages, documented in power electronics literature [3], justify the higher initial investment through extended equipment lifespan and reduced maintenance costs. For the Jado pumping station's operational requirements - involving sequential starts of multiple pumps - the Soft Starter proved most suitable despite its premium cost.

Our findings emphasize that motor starting method selection must consider:

1. Technical performance metrics
2. Economic factors (both initial and lifecycle costs)
3. Specific network conditions
4. Operational requirements

By using DOL method, only two motors could be started up simultaneously, while in the other methods the complete set of motors (5 motors) could be start up simultaneously

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