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Practical Transient State Assessment for Induction Motors Starting in Medium Voltage Networks

تقييم الحالة العابرة لبدء المحركات الحثية عمليا في شبكات الجهد المتوسط

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KEYWORDS:
Induction motor, Transient state, Dynamic model.

الملخص العربي: **- تقدم هذه الورقة نظام النمذجة مع التحقق بالتجارب المعملية لمجموعة من المحركات الحثية أثناء البدء في شبكات الجهد المتوسط بما في ذلك آثارها على وحدات التشغيل المجاورة الأخرى في ظروف التشغيل المختلفة .يعتمد نموذج المحاكاة على دراسة حالة واقعية وهي محطة ضخ الصرف الزراعي . تم بناء النموذج الديناميكي بواسطة MATLAB® / SIMULINK® حيث يمكن تحقيق تحليل شامل للأداء. بالنسبة إلى التحقق من النظام، تمت مقارنة نتائج المحاكاة ببيانات من واقع الحياة تم تسجيلها بواسطة جهاز مناسب موجود في موقع العمل. تم استخدام النموذج المتحقق منه لإجراء ستة سيناريوهات عملية استنادًا إلى إرشادات تشغيل المحطة الحقيقية .لكل سيناريو تمت دراسته، تتم مناقشة مجموعة من الخصائص مثل انخفاض الجهد، ومدته وتنظيم الجهد الخاص به بالتفصيل ومقارنته في شكل جدولي مع مراعاة التعديلات الموصى بها لإعدادات منظومة الحماية.**

***Abstract*— This paper presents a modelling and experimental verification system for a group of induction motors during starting in medium voltage networks including its effects on other nearby running units in different operating conditions. The simulation model is based on a real-life case study which is an agricultural drain pump station. The dynamic model was built with MATLAB®/SIMULINK® where a thorough performance analysis can be achieved. For system verification, the simulation curve results were compared with real-life data curves which were recorded by a suitable device located on worksite. The verified model was used to perform six practical scenarios based on the real station's operating instructions. For each studied scenario, a group of parameters such as voltage dip, its duration and voltage regulation are discussed in detail and compared in a tabular form considering the recommended adjustments for the protection relay settings.**

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I. INTRODUCTION

The induction motor is considered one of the most popular ac motors due to being used in several applications [1-3] such as water pumps (axial, centrifugal and axial-centrifugal), hoists, fans and compressors.

Due to its numerous uses and importance, it had the attention of researchers over the years [4-19]. In [5], the aspects of motor design are discussed illustrating its effects on starting period and the lifetime expectancy. In [6, 7], the starting methods of large motors with high inertia loading are presented and compared. In [8], a method to calculate the starting time of large induction motors is presented. In [9, 10], methods of soft starting the squirrel cage induction motor are provided and compared. In [11], the issue of starting performance if any one phase is interrupted during starting process is presented. In [12, 13], the effects of voltage sag and dips on the performance of induction motors are presented with experimental verification. In [14], the fundamentals of under-voltage protection are discussed to prevent false trips in case of open phase failures. In [15], MATLAB simulations are introduced to help in the assessment of transient state of induction motor. In [16], a MATLAB application is introduced to monitor the performance of electric machines. In [17, 18], good models for induction motor are presented then the performance of motor driving a pump load is analyzed and sketched. In [19], different methods to reduce the starting current of the induction motor are presented as well as energy and reactive power requirements are also discussed. And at no doubt, the research will still continue to further improve the motor performance under the steady state and transient operating conditions.

One of the major topics in the induction motor operation theory is the starting stage and the effects of transient state on power system network as well as other nearby running motors. In [20, 21], a d-q model for induction motor is developed, then the transient waveforms are illustrated with respect to different reference frames. In [22], an α-β model for induction motor was developed to facilitate studying stator behavior during source interruptions. In [23], an etap model was developed to show the effects of the incoming induction motor on a neighboring load by comparing different starting methods. In [24], effect of large induction motor on power system stability is studied with a practical test system.

Hence, this paper presents a theoretical study for a combination of medium voltage induction motors during starting stage as well as the effects of starting one motor or more on the running group accompanied by a practical study in a real-life case study (agricultural drain pump station). The case study was simulated using MATLAB®/SIMULINK® software where different practical scenarios can be simulated thoroughly. Also, real-life measurements were recorded using power analyzer equipment, and then they were compared with the simulations curve results for model verification purposes.

The main contributions of this paper are the comparison between the transient parameters for all scenarios which will help in coordinating the protection scheme settings.

The sections of this paper are divided as following; In section II, the sources, effects of the transient state and means of protection are illustrated. In section III and IV, the data of the case study is previewed, and the system model is introduced. In Section V, different case study scenarios are discussed and compared in a tabular form.

II. TRANSIENT STUDY

At a glance, the transient event is caused in power system when a sudden change occurs in the network or when the network changes from a certain steady state to another one. During the transient event, the system takes some time (normally few µs or ms) to get to its original or a new steady state. If the transient occurred due to abnormal reason, the system may not recover from the transient event and a general failure may occur to the system.

A. Classification of Power System Transients

1) According to source:

It is either internal (such as: switching, faults and sudden loading) or external (such as: lightning strokes) [25].

2) According to nature:

It is either due to electromagnetic nature (such as interference on control circuits) or electromechanical nature (such as the transient stability of synchronous machines where oscillations occur due to acceleration and de-acceleration around synchronous speed) [25, 26].

B. Sources and Effects of Transient

The transient event occurs when the system state is suddenly changed due to one or more than one of the following reasons that have different effects on the system, and they are listed in Table 1.

TABLE 1.
SOURCES AND EFFECTS OF TRANSIENTS.

Sources of transient	Effects of transient
Switching on and off system components	High striking voltage and inrush current values.
System faults	Excessive overcurrent current due to shunt faults (short-circuit). Excessive overvoltage due to series faults (open conductor).
Loading	Excessive overcurrent due to sudden high loading impact. Excessive undercurrent due to sudden high loading tripping.
Lightning strokes and arcs	Excessive voltage that could damage the insulations.

C. Protection Against Transient Effects

The transient events cannot be avoided completely, but their effects can be mitigated to save the stability of the system. Table 2 illustrates some of the possible means to help mitigating the effects.

TABLE 2.
MEANS OF PROTECTION AGAINST TRANSIENT EFFECTS.

Effects of transient	Means of protection
High striking voltage	Surge arrestors.
Overvoltage	Grading of insulators and cable raychems. Protective relays. Heaters inside panels and equipments to absorb moisture.
Overcurrent	Fuses. Current limiters. Protective relays with good coordination.

III. AGRICULTURAL DRAIN PUMP STATION

A. The Station's Overview

The case study of this paper is based on a real-life agricultural drainage water pump station as shown in Fig. 1 that operates using six identical 630 kW medium voltage three-phase induction motors with rheostatic rotor starter. The main units are loaded with a speed reduction gearbox which runs an axial-centrifugal type water pump with drainage capacity of 9 m3/sec and a head of 4.9 m. The case study was used for studying the starting of induction motor and to evaluate the transient state in a certain operating scenario.

Fig. 1. The six main units inside the station.

The following context will introduce a quick survey on the station's topology.

B. The Single Line Diagram

The station has four feeders 11 kV coming from the electrical substation, two mains are selected using two (2+1) ring main units (RMUs) only operated by electricity personnel, a medium voltage 11 kV panel receives the two incoming mains, since all the feeders are out of synchronism, an electrical interlock is implemented as precaution to either prevent switching on the bus coupler along with the two incoming lines switched on or only allowing one feeder on along with the bus coupler.

The medium voltage 11 kV panel distributes the power through transformers to two panels: a medium voltage 6 kV panel to operate the main units and a low voltage 380 V Panel to operate the station services including the battery charging panel.

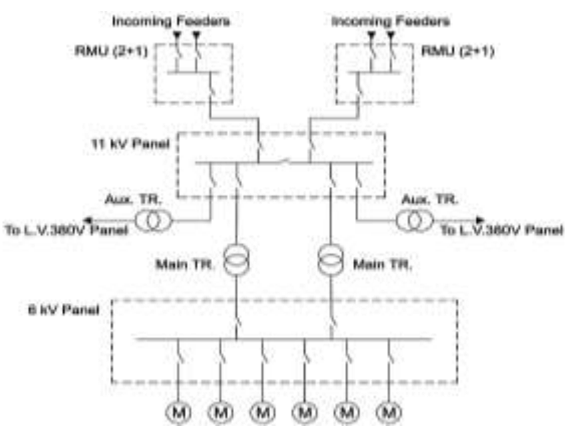

Fig. 2. The station's single line diagram.

The single line diagram shown in Fig. 2 presents a brief illustration of the power flow through the different components inside the station.

C. The Motor's Data

Every single main unit consists of a three-phase induction motor which is slip-ring (wound rotor) type that its rotor is connected externally through copper brushes to a rheostatic rotor starter. The motor is provided with a mechanism that keeps the slip-rings attached with the brushes during starting stage. As soon as, the starter completes its steps, the mechanism instantaneously lifts the brushes and inserts a short-circuiting end-ring into internal rotor's bars terminals. The motor's data that is listed in Table 3 was obtained from nameplate and routine tests that were performed on site. Also, the rheostatic starter data that is listed in Table 4 was extracted from the real-life one.

TABLE 3.
THE MOTOR DATA.

RMS (line to line) voltage	6000 V
Supply frequency	50 Hz
Reference frame frequency	50 Hz
Number of poles	4
Stator to rotor turns ratio	6000/890
Stator resistance	0.897597 Ohm
Rotor resistance referred to stator side	0.849943 Ohm
Stator leakage inductance	0.0170862 H
Rotor leakage inductance referred to stator side	0.0118289 H
Magnetizing inductance	0.55557 H
Rotor inertia	26 Kg.m^2
Mechanical friction constant	0.1277 N.m.sec

TABLE 4.
RHEOSTATIC STARTER DATA REFERRED TO STATOR SIDE.

R steps	Ohm	Time (sec)
R1	5.5	1.8
R2	3.5	2.8
R3	2.5	3.8
R4	2	4.8
R5	1.6	5.8
R6	1.2	6.8
R7	0.8	7.8
R8	0.6	8.8
R9	0.5	9.8

The last data can now be forwarded to be used inside the MATLAB dynamic model.

IV. SYSTEM DYNAMIC MODELLING

The system under discussion that is shown in Fig. 2 consists of six identical units which will be very complex if it is modelled exactly. Thus, the necessary components and units are only implemented according to each scenario requirements. The station's dynamic model block diagram is shown in Fig. 3. Also, the Unit 1 model block diagram is shown in Fig. 4. Both models were built using the MATLAB®/SIMULINK® software.

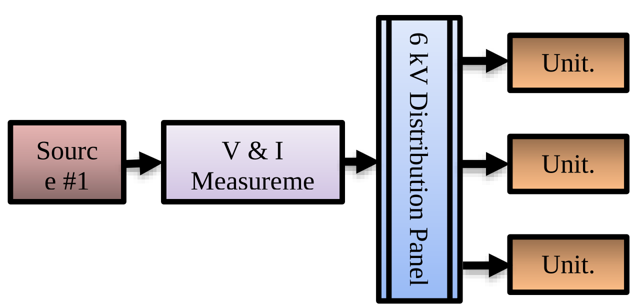

Fig. 3. The station's dynamic model block diagram.

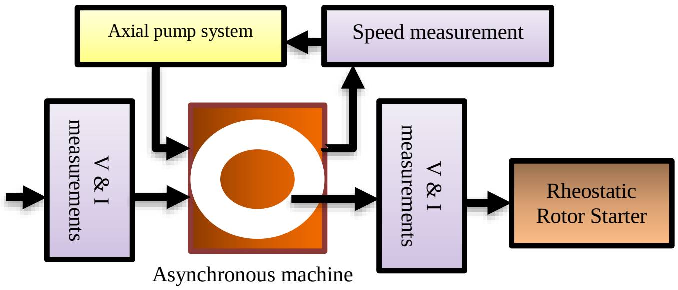

Fig. 4. The block diagram of the three-phase induction motor model (Wound Rotor) type with rotor starter (Unit 1).

V. Different Transient State Scenarios Of Case Study

The In this section, different scenarios are applied for the assessment of the transient state during the starting stage of induction motor in medium voltage networks. All of the following scenarios were done in simulation environment using the proposed system dynamic model of a real-life pump station. The selected scenarios are chosen according to a specific criterion which will be discussed in detail in each case.

In order to verify the validity of the proposed simulation model, the simulation results should be compared with experimental data. However, some of the scenarios study fault conditions that may impose the station's equipments to permanent damages if it is done in real-life. As a result, the applicable scenarios were only been performed on site to ensure the safety of station and operating personnel. The real-life data was recorded using the power analyzer equipment. Then, the data is compared later. The scenarios are illustrated as follows:

i. The First Scenario

According to the recommended operating instructions of the case study (agricultural water drain pump station). When the input suction level is low, two units should enter into service back to back. This is the criteria which the first scenario is based on.

In case of starting one of the units alone (Unit 1). After reaching its steady state, Unit 2 is suddenly allowed to start at the arbitrary instance of 12 sec of simulation time. The Simulink results and power analyzer measurements are shown next. Also, the transient parameters are summarized in Table 5 (Row 1).

For Unit 1, instantaneous, RMS current and electromagnetic torque curves are shown in Fig. 6, 7 and 8 respectively. The total instantaneous and RMS supply current are shown in Fig. 9 and 10 respectively.

A. Simulation Data Analysis

It is remarkable that the switching instance caused a small ripple on stator current and torque curves for Unit 1 as shown in Fig. 6, 7 and 8 respectively which had minimal disturbance to its stability and operation. Also, the power analyzer measurements for total supply current nearly match the ones from Matlab/Simulink as shown in Fig. 9, 10, 12 and 13.

It is remarkable that a small second harmonic is introduced in the signal of total supply current as shown in Fig. 5. It is due to the nature of induction machine's inrush current. It lasts only during the whole starting period until the rotor starter is completely out of its circuit.

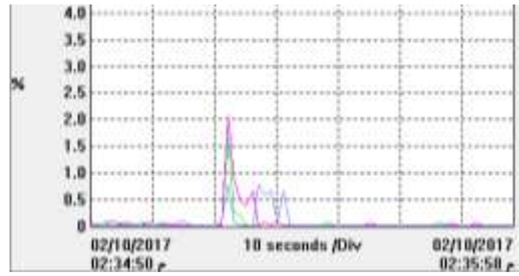

Fig. 5. The second harmonic percentage inside the total supply current signal (Power analyzer).

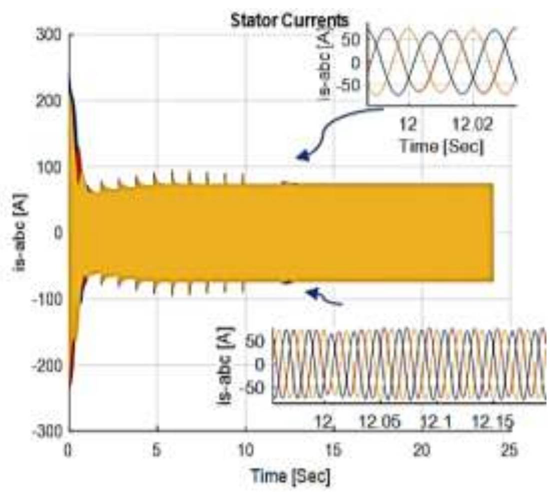

Fig. 6. The instantaneous current waveform for Unit 1 (Scenario 1).

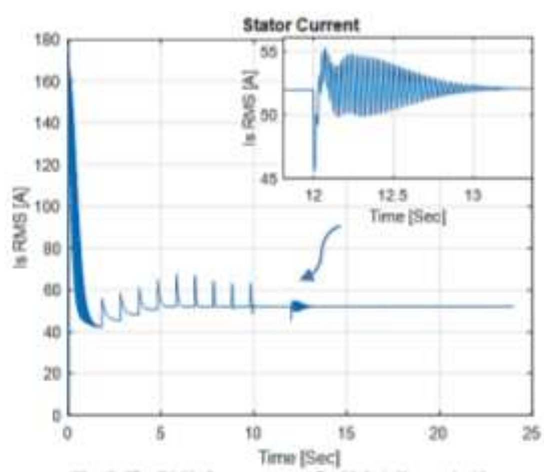

Fig. 7. The RMS drawn current for Unit 1 (Scenario 1).

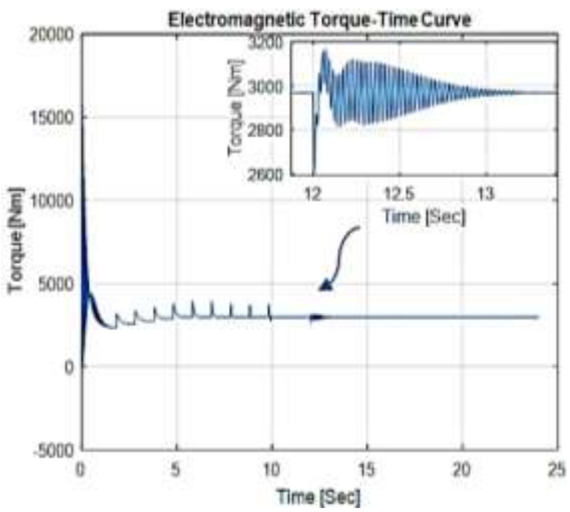

Fig. 8. The developed electromagnetic torque for Unit 1 (Scenario 1).

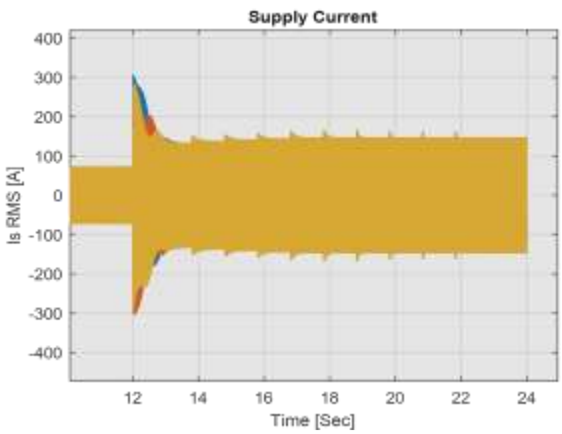

Fig. 9. The total instantaneous supply current for both Units 1 and 2 (Scenario 1).

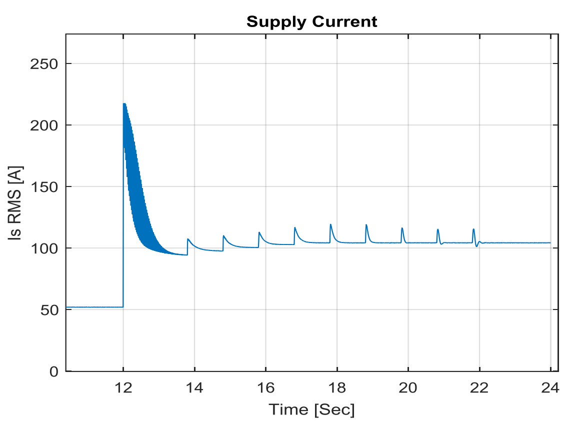

Fig. 10. The total RMS supply current for both Units 1 and 2 (Scenario 1).

B. *Power Analyzer Data Analysis*

It is remarkable that the switching instance also caused a small voltage dip followed by continuous small drop in the RMS (L-L) voltage curve as shown in Fig. 11. The voltage dip is due to the excessive kVAR consumed by motor during switching instance as shown in Fig. 15 also known as the inrush stage. After catching speed and the transition into steady state stage, the normal kVAR power loading of motor will result in a continuous small voltage drop.

Since, Unit 2 is started with full pump loading applied (around 450 kW), the required kW is delivered instantaneously to the starting unit as shown in Fig. 14.

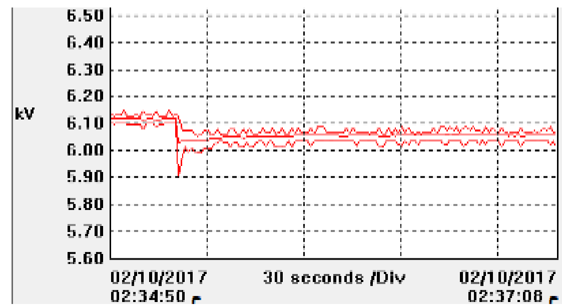

Fig. 11. The RMS supply voltage (L-L phases) for both Units 1 and 2 (Power analyzer).

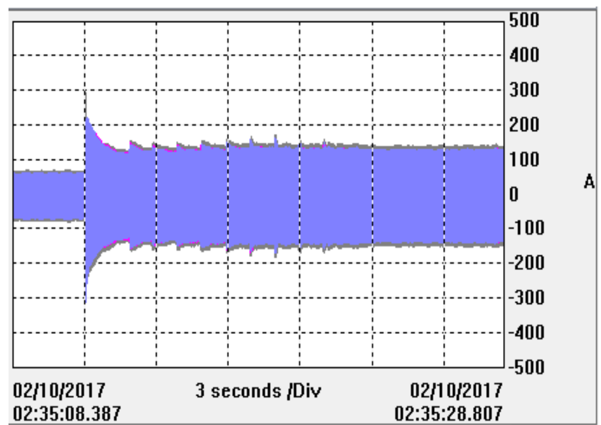

Fig. 12. The total instantaneous supply current for both Units 1 and 2 (Power analyzer).

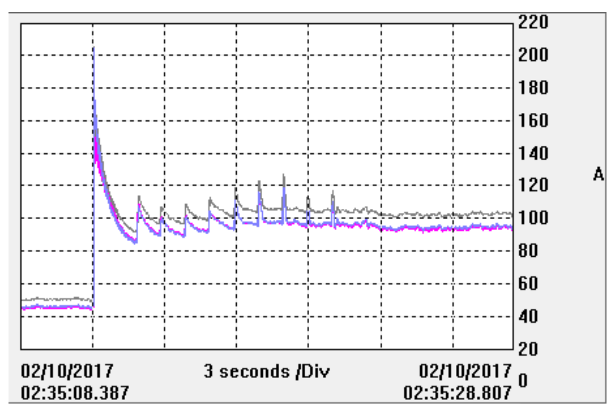

Fig. 13. The total RMS supply current for both Units 1 and 2 (Power analyzer).

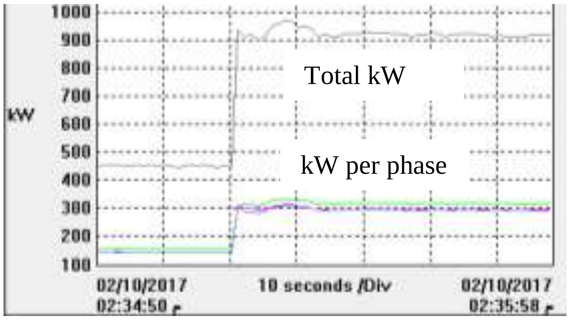

Fig. 14. The total kW power drawn for both Units 1 and 2 (Power analyzer).

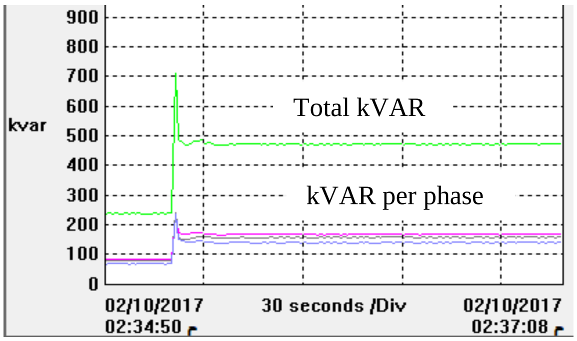

Fig. 15. The total kVAR power drawn for both Units 1 and 2 (Power analyzer).

ii. THE SECOND SCENARIO

In this scenario, when the input suction level is medium, three units should enter into service back to back according to the station's operating instructions.

In case of only are two units running together (Units 1 and 2), after reaching their steady state, Unit 3 is suddenly allowed to start at the arbitrary instance of 12 sec of simulation time. The Simulink results are shown in Fig. 17 (Table 5, Row 2).

iii. THE THIRD SCENARIO

For the present scenario, when there is emergency state and the input suction level is becoming too high to be handled by the currently running units, the operating personnel are obligated to start the maximum permissible number of units simultaneously.

In case of one of the units is started alone (Unit 1), after reaching its steady state, Units 2, 3, 4 and 5 are suddenly allowed to start at the arbitrary instance of 12 sec of simulation time. The Simulink results are shown in Fig. 18 (Table 5, Row 3).

iv. THE FOURTH SCENARIO

In this scenario, the open phase fault is introduced by showing its effect on the currently running units. When the suction level is high, but the currently running units are insufficient. Thus, one more unit is allowed to enter into service according to the station's operating instructions.

In case of only are four units running together (Units 1, 2, 3 and 4), after reaching their steady state, Unit 5 is suddenly allowed to start at the arbitrary instance of 12 sec of simulation time with two phases only due to an open conductor fault condition. The Simulink results are shown in Fig. 19 (Table 5, Row 4).

v. THE FIFTH SCENARIO

The criterion of this scenario is similar to the second scenario; however the upcoming unit has a random L-G fault condition on its terminal.

In case of only are two units running together (Unit 1 and 2), after reaching their steady state, Unit 3 is suddenly allowed to start at the arbitrary instance of 12 sec of simulation time with a L-G fault. The Simulink results are shown in Fig. 20 (Table 5, Row 5).

vi. THE SIXTH SCENARIO

The three-phases (L-L-L-G) fault is considered the most severe one in the power system. Although, it is very rare to happen, it may occur in the system under study due to forgetting earthing switch on after a certain maintenance in the upcoming unit. So, this scenario will illustrate the system response under such a rare circumstance.

In case of only are two units running together (Unit 1 and 2), after reaching their steady state, Unit 3 is suddenly allowed to start at the arbitrary instance of 12 sec of simulation time with a L-L-L-G fault on its terminal. The Simulink results are shown in Fig. 21 (Table 5, Row 6).

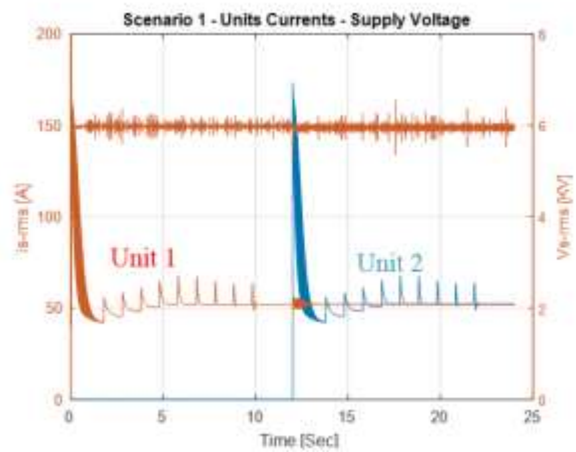

Fig. 16. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1 and 2 (Scenario 1).

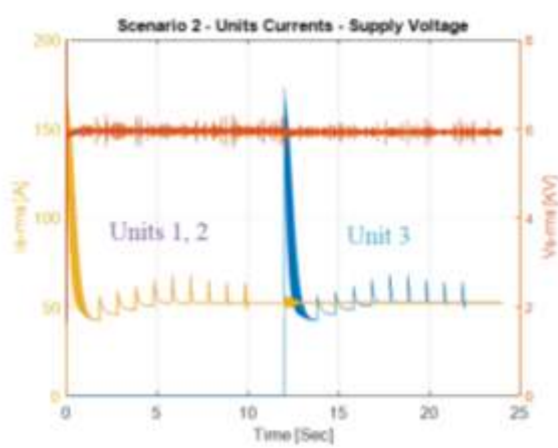

Fig. 17. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1, 2 and 3 (Scenario 2).

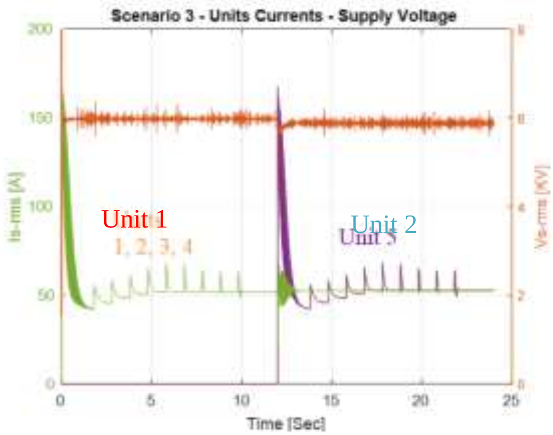

Fig. 18. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1, 2, 3, 4 and 5 (Scenario 3).

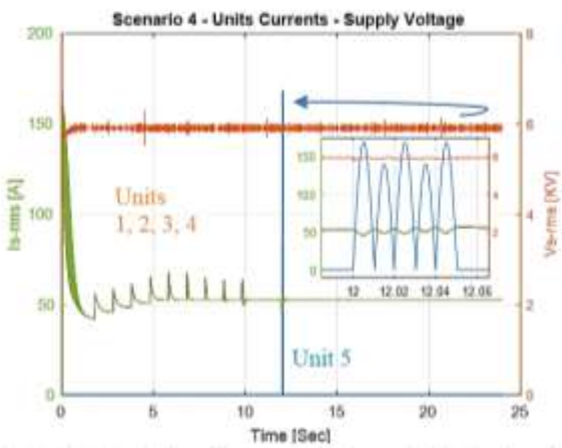

Fig. 19. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1, 2, 3, 4 and 5 (Scenario 4).

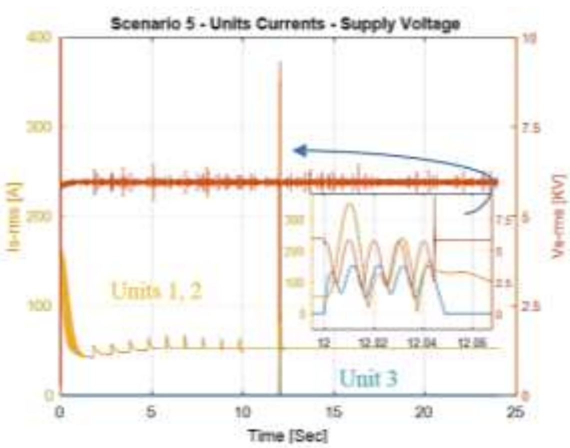

Fig. 20. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1, 2 and 3 (Scenario 5).

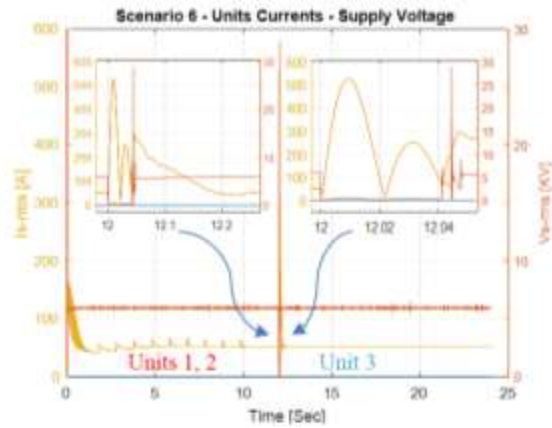

Fig. 21. The RMS plotting of line current plus the terminal (L-L) voltage for Units 1, 2 and 3 (Scenario 6).

VI. Transient Data Discussion

The developed model was used to compile different practical scenarios that were chosen according to the station's operation dairy and operating instructions. The assessment in scenario one, two and three illustrated the effects of transient state for incoming unit on the current and voltage signals of supply while another unit is running nearby. It is remarkable that the more units are switched on together, the more the voltage dip percentage and duration increase as shown in Table 5, Rows 1-3 (it ranged between 9 ~ 31 % for 4 ~ 6 msec).

On the other hand, the rest of the scenarios introduced the effects of practical faults that may occur to the system. In scenario four, the open phase fault proved to have the least impact on the running system as it had the voltage dip percentage (around 2%) and minimal disturbance duration time on the nearby units (around 300 msec). However, the upcoming unit failed to start, and it must be tripped as soon as possible. In this case, the recommended trip time setting on the digital protection relay (I2> stage) is to be adjusted 0.04 sec to avoid any sustained fault effects and equipment damages.

At last, the most critical phase faults were presented in scenarios five and six which a brief voltage collapse was noticed before clearing the fault (it ranged between 10 ~ 100 % for 40 ~ 100 msec). In this case, imminent system failure is very close for any delayed fault clearing. Thus, the recommended trip time setting on the digital protection relay (I>> stage) is to be adjusted no more than 0.04 sec to avoid any sustained fault effects and equipment damages.

VII. Conclusion

This paper presented a theoretical-practical study in the transient state assessment for induction motor starting in medium voltage networks based on a real-life case study which is an agricultural water drain pump station. A quick discussion on the transient study was made including the types, sources of transient and protection means. The assessment was performed in simulation environment using the MATLAB/Simulink software where the station's model was developed. The model validity was verified by comparing the simulation curve results with those that were recorded using a power analyzer equipment that was installed on-site by authors. The verified model was used to compile different practical scenarios that were chosen according to the station's operation dairy and operating instructions. The first three scenarios have proven that the more units are switched on together, the more the voltage dip percentage and duration increase. Lastly, the last three scenarios that deal with faults, the recommended trip time setting on the digital protection relay (I2> and I>> stages) is to be adjusted 0.04 sec to avoid any sustained fault damages.

TABLE 5.
SUMMARY MATLAB DATA OF TRANSIENT PARAMETERS FOR ALL SCENARIOS.

Scenario Number	**Switching Sequence**	**Voltage Dip %**	**Voltage Dip Duration Time (msec)**	**Voltage Regulation %**	**Nearby Units Current Disturbance Duration Time (msec)**
1	Unit 1 is running. Unit 2 is started at an arbitrary time.	9.07	4	0.41	1500
2	Units 1 and 2 are running. Unit 3 is started at an arbitrary time.	8.67	5	0.42	1600
3	Unit 1 is running. Units 2, 3, 4 and 5 are started at an arbitrary time.	31.86	6	1.67	1200
4	Units 1, 2, 3 and 4 are running. Unit 5 is started at an arbitrary time with two phases only.	2.12	6	0.54	300
5	Units 1 and 2 are running. Unit 3 is started at an arbitrary time with a L-G fault on its terminal.	10.12	100	33.64	150
6	Units 1 and 2 are running. Unit 3 is started at an arbitrary time with a L-L-L-G fault on its terminal.	100	40	95.43	300

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