Analysis for the Effects of Grid Voltage Degradation on APR1400 Operation, Case Study for Egypt

Mostafa Ahmed Fouad Hassan[1*], Chang Choong-koo[2]
[1&2]Nuclear Power Plant Engineering Department, KEPCO international Nuclear Graduate School, 658-91 Haemaji-ro, Seosang-myeon, Ulju-gun, Ulsan 689-882, Korea
[*]Corresponding author, Email: mostafaahmedfouad@hotmail.com

1. Introduction

The safe and economic operation of the nuclear power plant (NPP) requires that the plant to be connected to a stable and reliable electrical grid where the voltage and frequency can be controlled within predefined limits. For a country that introduces NPP for the first time, such stable and reliable gird may not exist and the grid may require extensive modification to be suitable for the connection of the NPP. Egypt is one of the countries planning to introduce a NPP into its electrical power system. Although the Egyptian power system has sufficient capacity to integrate any commercially available nuclear unit as the total installed capacity of the power system is more than 32GWe [1], which is more than 10 times capacity of any nuclear unit in the range of 1000 to 1700MWe, the system is vulnerable to extreme voltage variations, especially voltage degradation during peak load conditions. These conditions can lead to voltage collapse if a counter measure, usually load shedding, is not taken in a proper time. Hence, it is necessary to analyze the effect of such conditions on the safe and economic operation of the NPP. In this paper we analyzed the effects of grid voltage degradation on the safe and economic operation of the Advanced Power Reactor (APR1400) to determine any adverse effects on the plant auxiliary loads while operating in the Egyptian power system.

2. Grid Requirements

Most grids have a requirement for power plant to be able to operate for a defined range of voltages. A typical requirement is to be able to operate indefinitely at full power for ± 5% about nominal voltage and to operate for a limited time, on a few occasions per year, possibly at reduced output, for a range of voltage outside the normal range, for example ±10% about nominal voltage [2]. For most grid systems this encompasses the full range of variation of grid voltage that is possible without voltage collapse. Nuclear plants should be designed to meet these grid requirements.

2.1 European Utility Requirements (EUR)

The European Utility Requirements for light water reactor nuclear power plants gives an example for grid requirements in European countries. EUR requires that the plant should be able to operate continuously at voltage level between 90% and 105% of nominal value and to operate at least for 30 minutes at voltage level below 90% of nominal value and once per 10 years for at least 30 minutes at voltage level above 105% of nominal value. Power reduction due to frequency deviation is permitted as illustrated in Figure1.

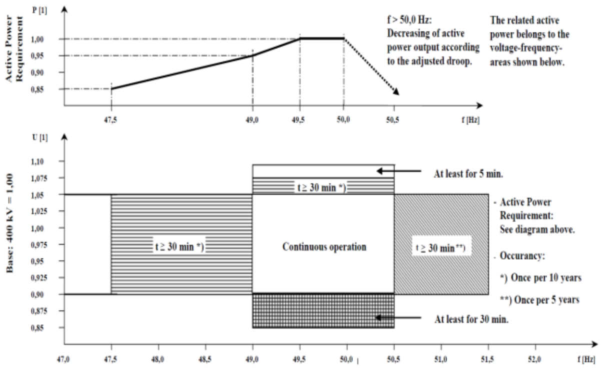

Fig. 1. Voltage and frequency operation fields for light water reactor NPPs as specified in EUR.

2.2 Egyptian Grid Characteristics

The main power system in Egypt consists of 500kV, 220kV, and 132kV transmission networks which supply power at 50 Hz.

According to the Egyptian Electricity Transmission Code (Grid Code) which is still under revision, the voltage variations in the grid shall remain within ±5% of the nominal value during normal conditions and ±10% during single contingency outages. In addition, voltage may temporarily exceed ±10% during severe grid emergencies and restoration. Table I shows example of 500kV grid voltage values during peak load condition.

Table I: Example of 500kV grid voltage values during peak load condition

Substation/Switchyard	Voltage(kV)	p.u. (500kV)
Cairo 500	433	0.866
Cairo west 500	431	0.862
Basous	433	0.866
Abo Zabal	440	0.88
Suez 500	460	0.92
A. Mousa	468	0.936
Kurimat	455	0.91
Assuit 500	440	0.88
Nobaria	448	0.896
Samalout 500	452	0.904
N. Hamadi	470	0.94
High Dam	490	0.98

In the previous example, we can notice that the voltage at the 500kV grid can degrade up to 86% of the nominal value during peak load conditions which usually last for more than one hour per day during summer season. Hence, the plant operation at this condition should be analyzed to determine any detrimental effect on the plant auxiliary loads.

3. Generator Requirements

Generators are designed to operate continuously and deliver the nameplate kVA rating at any voltage between ±5% of their rated voltages. According to IEEE Standard C37.102-2006, "Guide for AC Generator Protection,'' operating a generator with terminal voltage lower than 95% of its rated voltage may result in undesirable effects such as reduction in stability limit, import of excessive reactive power from the grid to which it is connected, and malfunctioning of voltage sensitive devices and equipment. This effect however is a function of time.

If operating at lower than 95% of rated voltage, the generator kVA output must be decreased from the normal value shown on its capability curve. When operating the generator overexcited (lagging power factor), the kVA output should be reduced proportionally to the voltage reduction (e.g., 90% kVA at 90% voltage). However, when operating generator under excited (leading power factor), the kVA output should be reduced proportionally to the square of the voltage reduction (e.g., 81% kVA at 90% voltage).

The generating unit in the nuclear power plant assists in controlling the local grid voltage by suppling or consuming reactive power, consequently, if the generator is tripped because of a low grid voltage, the local grid voltage will fall further, and if the tripping is combined with that the generator is set up to produce maximum reactive power, the grid voltage will fall further and may lead to voltage collapse. Hence, the loss of generating units due to tripping of the undervoltage functions or operator action during a recoverable extreme system event must be avoided. A recoverable extreme system event is defined as a transmission system voltage at the high-side of the generator transformer of 0.85 per unit [3].

Tripping units on undervoltage is not recommended by the IEEE Standard C37.102. Instead C37.102 recommends an alarm to alert the operator to the abnormal conditions that require operator intervention.

3. Nuclear Safety Requirements

The general design principles for NPPs require that the reactor can remain safely at power for a range of expected variations in grid voltage. Limitations that are determined during design are stated for highest level of power system (Class 1E power system). Class 1E power system has a vital role of supplying the necessary power to the safety systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and preventing significant release of radioactive material to the environment. These safety systems are designed for continuous operation within limited voltage variations from the nominal values. Hence, voltage at Class 1E buses (safety related buses) must be controlled within a defined narrow range.

United States Nuclear Regulatory Commission (USNRC) - Branch Technical Position (BTP) 8-6 requires that the voltage levels at the safety-related buses should be optimized for the maximum and minimum load conditions that are expected throughout the anticipated range of voltage variations of the offsite power sources by appropriate adjustment of the voltage tap settings of the intervening transformers [4]. In addition, two levels of undervoltage detection and protection should be provided on the Class 1E electrical distribution system. One level of undervoltage protection is provided by the degraded voltage relays, which are set to detect a low-voltage condition in order to maintain 90% bus voltage at the Class 1E Motor Control Centers. These relays alarm to alert the operators to the degraded condition and disconnect the Class 1E buses from the preferred power supply (grid) if the degraded voltage condition exists for a time interval that could prevent the Class 1E equipment from achieving its safety function or from sustaining damage due to prolonged operation at reduced voltage. The other level of undervoltage protection is provided by the loss of voltage relays whose function is to detect and disconnect the Class 1E buses from the preferred power supply upon a total loss of voltage [5].

4. APR1400 Electrical Power System Simulation

In order to evaluate the effect of grid voltage degradation on APR1400 operation, the main and auxiliary power systems of APR1400 unit and its connection to the 500kV Egyptian power system were modeled in detail using the Electrical Transient Analysis Program (ETAP 12.6.0). Figure 2 shows the main configuration of APR1400 electrical power system (division I).

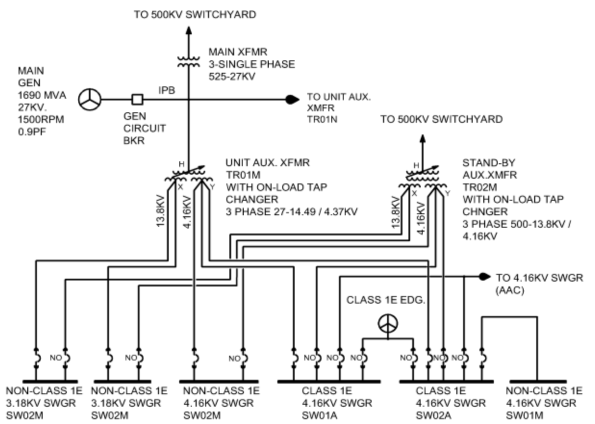

Fig. 2. Main configuration of APR1400 electrical power system (division I)

The following is a brief description of the main and auxiliary power systems and the various voltage levels utilized in APR1400.

4.1 Main Power System (MP)

The main power system consists of the Main Generator, Isolated Phase Bus (IPB), Generator Circuit Breaker (GCB), and Main Transformer (MT). The primary function of the MP system is to generate power at 27 kV (generator rated voltage) and transmit it to the 500kV transmission system while simultaneously supply power to the unit auxiliaries.

4.2 Auxiliary Power System (AP)

The auxiliary power system is divided into two divisions, each division includes one Unit Auxiliary Transformer (UAT) and one Standby Auxiliary Transformer (SAT). During normal plant operation, each UAT provides power to two non-Class 1E 13.8 kV switchgears, two Class 1E 4.16 kV switchgears, and two non-Class 1E 4.16 kV switchgears, each switchgear provides power to large motors and associated 480 V load centers. Connected loads to the load centers are motors, heaters and 480 V motor control centers. Table II shows the various voltage levels utilized in the auxiliary power system and the associated loads.

Table II: APR1400 Auxiliary power system voltage levels and associated loads

Voltage Level	Loads
13.8 kV System	Motors rated for 1,500 HP and larger
4.16 kV System	Motors rated for 250 HP to 1250 HP
480 V LC	Motors rated for 60 HP to 225 HP
480 V MCC	Motors rated for 0.5 HP to 60 HP, all MOVs, lighting transformers, and the control rod drive motor generator sets
120 V System	Motors rated for 0.5 HP and less

Voltage levels at the auxiliary power system buses are maintained within acceptable range by automatic adjustment of the voltage tap settings of the UATs or SATs. The characteristics of the tap changers are as follows: high voltage side, on-load tap changers (OLTCs), ±1.25% x 8 steps.

5. APR1400 Operation Modes

Since the minimum operating voltages is the main interest of this analysis, the plant maximum loading conditions were considered for the load flow analysis. Generally, normal operation and Loss of Coolant Accident (LOCA) are considered as the maximum loading conditions for the plant.

5.1 Plant Normal operation

After the main transformer is connected to the offsite power grid by closing the switchyard circuit breakers, the offsite electrical power is supplied to the plant auxiliary loads via the main transformer and unit auxiliary transformers with the generator circuit breaker open. Once the turbine generator is brought up to, or near its synchronous speed (1500 rpm) and the generator is synchronized to the grid, the generator circuit breaker is closed and the generator output can be increased gradually up to its rated power so that all plant loads can be supplied by the generator rather than by the grid.

5.2 LOCA condition

Although it is unlikely event, LOCA condition is one of the most severe conditions for the plant auxiliary power system. Upon receiving LOCA signal, all required medium voltage motors will sequentially started and all required low voltage motors will be accelerated simultaneously [6]. In addition, due to reactor trip, the main generator becomes unavailable to support reactive power required by the grid which may lead to further degradation in gird voltage. Hence, it is important to ensure the adequacy of voltage at all safety related medium voltage and low voltage buses during this condition.

6. Motors Voltage Constraints

Motors of various rated voltages are utilized in the plant auxiliary systems and constitute the majority of the loads. The rated voltage of the motors is less than the bus rating that feed them. The rated voltage of large motors fed from 13.8 kV and 4.16 kV switchgears are 13.2 kV and 4.0 kV respectively. Motors fed from the load centers and motor control centers have a rated voltage of 460 V.

The voltage limits for motor operation are as follows: during steady state operation, the maximum motor voltage at any time shall be limited to a value no greater than 110% of rated motor voltage with the system voltage at maximum expected value and transformer loading at minimum value. The minimum motor voltage shall be limited to value no less than 90% of rated motor voltage during normal operation, assuming minimum system voltage and all transformers loaded to maximum capacity.

Motors starting voltage shall be 80% or greater on the motors being started and on the motors already running, for 13.2kV and non-Class 1E 4.0kV motors.

For Class 1E motors, USNRC Regulatory Guide 1.9, Position C.1.4 specifies that “the diesel generator unit design should be such that at no time during the loading sequence should the frequency and voltage decrease to less than 95 percent of nominal and 75 percent of nominal, respectively''[7]. Hence, Class 1E motors should be capable of accelerating their loads within the required time at the 75% of rated motor voltage.

7. Effects of Degraded Voltage Condition on Motors

Degraded voltage condition is of primary concern with motor protection. The effect the degraded voltage condition has on any given motor will vary depending on the type of motor, the driven load, and whether the motor is running or being started. While the motor is running if the voltage decrease, the current drawn by the motor will increase causing motor operating temperature to increase. Motor operating temperatures will determine the life of the motor insulation. Each occurrence of increased temperature will effectively reduce the life of the motor. It is, therefore desirable to detect these conditions as soon as possible to limit the loss of motor life.

Too low voltage at the terminals of a motor while the motor is being started may prevent it from reaching its rated speed, or cause the acceleration period to be extended, resulting in excessive heating of the rotor and stator windings. As example, accelerating time for 900 hp Safety Injection (SI) pump motor at the 4.16 kV safety related bus is approximately 3 seconds at 75% voltage versus 1.2 second at 100% voltage as shown in Figure 3.

Voltage degradation during pump starting is a safety concern if the condition delays the flow beyond times used for accident analysis in the plant safety analysis report.

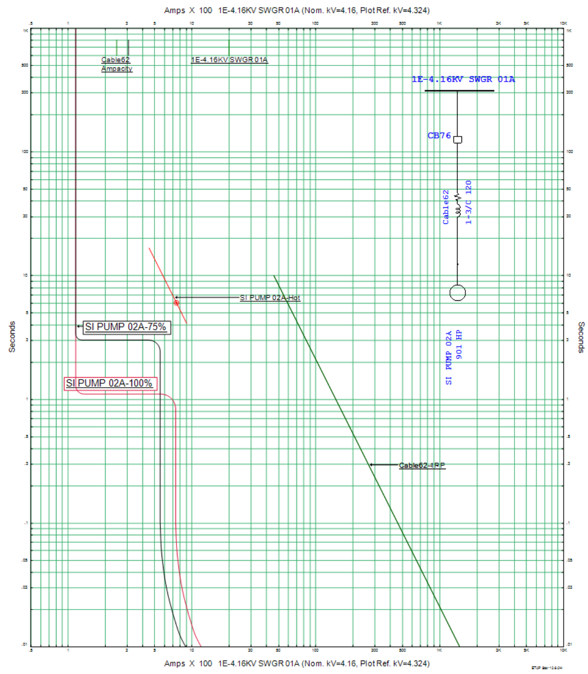

Fig. 3. SI pump motor starting time current characteristics at 100% and 75% voltage.

7. Load Flow Analysis

A Load flow analysis for the electrical power system of APR1400 was conducted using ETAP 12.6.0 taking into account the Egyptian grid characteristics, generator operating limits, plant safety requirements, operation modes and loading categories.

The switchyard voltage was set at 100%, 95%, 90%, and 85% of the nominal value (500kV). This includes the minimum expected value for grid voltage during peak load conditions. The analysis was conducted for normal operation mode and LOCA condition which represent the maximum loading conditions for the plant. The results of load flow analysis show that the minimum value for the distribution voltage exists at the safety related 4.16kV bus (SW01A) and 480V Motor Control Center (MC05A). Tables III & IV show the results of the load flow analysis at different values of switchyard voltage for normal plant operation and LOCA condition respectively.

Table III: Load flow result for normal operation

Switchyard voltage %	100	95	90	85
Generator voltage %	99.94	95.87	91.94	87.6
Generator MW	1518	1518	1518	1518
Generator MVAR	592.8	646.6	711	739
UAT Tap%	0	-3.75	-7.5	-10
4.16kV SW01A%	98.8	98.43	98.2	95.9
4.0kV Motor V_{tr}%	102.3	101.9	101.7	99.3
480V MC05A%	94.52	93.63	93.39	91.0
460V Motor V_{tr}%	97.65	97.24	96.66	94.5

Table IV: Load flow result for LOCA condition

Switchyard voltage %	100	95	90	85
UAT Tap%	-6.25	-10	-10	-10
4.16kV SW01A%	97.92	96.61	90.46	84.2
4.0kV Motor V_{tr}%	101.4	100.1	93.64	87.1
480V MC05A%	93.14	91.76	85.28	78.6
460V Motor V_{tr}%	96.72	95.27	88.48	81.5

The load flow result for normal operation shows that, during grid voltage degradation, the generator attempt to maintain its terminal voltage and increase the MVAR output to compensate for the shortage of reactive power which is the main cause of grid voltage degradation. This is done by the automatic voltage regulator (AVR). In addition the on load tap changers on the UATs automatically adjust their turns ratio so as to maintain the distribution system voltage within acceptable limits. The generator produces its max reactive power and the OLTCs reach their minimum taps (-10%) at 85% of the switchyard nominal voltage.

In case of LOCA condition the plant protection system will generate a signal to:

- Trip the reactor and the turbine generator,

- Start the Emergency Diesel Generators (EDGs) whether needed or not,
- Start the required safety loads by sequencing them to Class 1E 4.16kV buses which are still powered form the offsite power supply.

During LOCA condition, if the switchyard voltage degraded below 95% of nominal voltage, the voltage value at Class 1E 4.16kV bus (SW01A) will degrade to 95% which is the setting value for degraded voltage relays. These relays will alarm to alert the operator to the degraded voltage condition. If degraded voltage condition continued for more than 4 minutes, the relays will send a signal to:

- Trip the supply breaker (disconnect the Class 1E bus from the offsite power supply),
- Trip the associated 4.16 kV motor feeders,
- Reset the load sequencer,
- Close the EDG circuit breaker,
- Restart the required safety loads by sequencing them on the EDG.

The process of starting, tripping, and restarting the safety loads is known as “*double sequencing*” and it has no adverse effects on the plant safety loads [8].

8. Motor Starting Analysis

The motor starting analysis was performed to ensure that the safety related motors required for LOCA condition can be started and accelerated to their rated speed during degraded voltage condition. The Auxiliary Feed Water (AFW) pump motor of 1173 hp is the largest motor could be required to start during LOCA condition. Table V shows the result of the AFW pump motor starting analysis at 85% of the switchyard nominal voltage.

Table V: Result of AFW pump motor starting analysis.

Switchyard voltage %	85
4.16kV SW01A%	82
4.0kV Motor V_{tr}%	85.1
480V MC05A%	76.21

Based on the above result, it can be demonstrated that the voltage value during the starting of the largest motor is maintained above the minimum acceptable limit (75% of motor rated voltage). Hence, the safety related motors required for LOCA are able to start and accelerate their loads even at the worst degraded grid voltage conditions.

9. Conclusions and Recommendations

In this paper the effects of grid voltage degradation on the safe and economic operation of APR1400 were investigated taking into account, generator operating limits, plant safety requirements, operation modes and loading categories in order to determine any adverse effect on the plant auxiliary loads while operating in the Egyptian power system.

The results of the load flow and motor starting analysis demonstrated that during normal operation the automatic voltage regulator and transformers OLTCs can mitigate the effect of grid voltage degradation without any detrimental effect on the plant auxiliary loads. During the highly unlikely LOCA condition if the grid voltage degraded below 95%, the degraded voltage relays at Class 1E 4.16 kV buses will trip the supply and load breakers and reconnect the required safety loads to the EDG after 4 minutes time delay. During this period the safety loads required for LOCA can be started and accelerated to their rated speed safely even in the worst case of expected degraded voltage condition. It can be concluded that, in all cases there is no detrimental effect on the plant auxiliary loads. However, operating the generator with terminal voltage lower than 95% of its rated voltage during plant normal operation may result in undesirable effects such as reduction in stability limit which is a function of time. Therefore, it is strongly recommended that the degraded grid voltage condition to be limited to -10% of the grid nominal voltage for a short periods. In general, reactive compensators with automatic controls can be used to compensate for reactive power imbalance during peak load conditions, which is the main cause of grid voltage degradation.

Further study is required to assess the grid voltage stability and to identify the proper solutions for degraded voltage condition.

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