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. Effect of Voltage SAG on the Performance Analysis of Synchronous Generator

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ABSTRACT: Voltage sag is a momentary reduction in root mean square(r.m.s) value of supply voltage to a value that lies between 0.1 and 0.9, which lasts from half a cycle at power supply frequency to one minute. This phenomenon imposes a bad effect on domestic and industrial loads, especially on torque pulsations of synchronous generator which can damage the shaft or equipment connected to the generator. It is therefore important to know these effects by recognizing the critical voltage sags as to prevent a sag that produces hazardous torque variations on generator. This paper presents the effects of voltage sags on the performance analysis of a synchronous generator by employing stochastic prediction methods for estimating the number of voltage sags using fault positioning method. In order to observe the validity of the method, computer simulation was used in which a synchronous generator is subjected to different types of voltage sags. The results reveal that during normal condition, generator voltages remain constant. During the voltage sag, the generator terminal voltage varies at different sag duration and magnitude, thus causing a fault to occur at the load terminal of the generator. The results indicate that the fault generated at the load terminal by the sag have more intensive effects on the synchronous generator torque pulsations. The effectiveness of the method used depends upon the rating of sag magnitude, sag duration and percentage voltage sag. The results obtained can provide the cost effective solution to mitigate voltage sag by establishing the appropriate voltage quality level required by the generator.

KEYWORDS: Stochastic Prediction, Fault Positioning, Synchronous Generator, Torque Pulsations, Voltage Sag. Sag Magnitude, Sag Duration.

I. INTRODUCTION

Voltage sags are one of the most frequent phenomena in power system. They are short duration reductions in root mean square (r.m.s) voltage caused by faults in electric power systems, load variations and the starting up of large machine [1]. This phenomenon affects the proper operation of end users. Voltage sag occurs on both on distribution voltages and transmission voltages. The severity of the sag depends on the amount of fault current available at that feeder. Voltage sags which occur at higher voltages will normally spread through a utility system and will be transmitted to lower voltage systems via transformers. Voltage sags can be created within an industrial complex without any influence from the utility system. These sags are typically caused by starting large motors or by electrical faults inside the facility [[12], [20]].

Voltage sag is not a complete interruption of power but a temporary drop of supply voltage in which the voltage delivered to the consumer is not at the rated voltage. Voltage sag is generally characterized by depth and duration [9]. The depth of the sag depends on the system impedance, fault distance, system characteristics (grounded or ungrounded) and fault resistance. The duration of the sag depends on the time taken by the circuit protection to clear the fault. High speed tripping is desired to limit the duration of sags [13]. The measurement of voltage sag is stated as a percentage of the nominal voltage which is a measurement of the remaining voltage and is stated as a sag to a percentage value [18].

Voltage sags typically appear when there is an abrupt increase in load such as starting large motor loads. It also appears after symmetrical and asymmetrical faults, motor starting, load switching or transformer energizing [11]. Weather such as lightning, animal contact, contamination of insulators, construction accidents, motor vehicle accidents, falling or contact with tree limbs also contribute to voltage sags. A short circuit fault is a typical cause of voltage sag. Single line to ground faults on the utility system is the most common cause of voltage sags in an industrial plant [15]. Voltage sags which can cause equipment impacts are usually caused by faults on the power system. Motor starting results in voltage sags but the magnitudes are usually not severe enough to cause equipment mis-operation [21].

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Loads such as adjustable speed drives, process control equipment and computers are sensitive to these voltage sags. These loads may trip or mis-operate even for voltage sag of 10% and lasting two cycles [26]. Industry applications such as paper mills and semiconductor fabrication plants take a lot of time to restart when tripped. Since they are production oriented, the impact of the voltage sag is enormous. Voltage sags are quite common in modern power systems and generally caused by motor starting, transformer energizing, pulsed load switching and electrical faults [5]. The depth of the sag depends on the electrical distance to the point of cause. The consequences of this are significant economic losses to the customer due to loss of production, idled labour and other ancillary costs, such as, those related to damaged equipment and penalties due to late delivery of products [[4], [17]].

Voltage sags and momentary power interruptions are probably the most important power quality problems affecting industrial and large commercial customers. These events are usually associated with a fault somewhere on the supplying power system [3]. Actual interruptions occur when the fault is on the circuit supplying the customer. Voltage sags are much more common since they can be associated with faults remote from the customer. Voltage sags lasting only 4-5 cycles can cause a wide range of sensitive customer equipment to drop out [2]. Analysis of voltage sag requires a knowledge of the voltage sag characteristics, statistical information describing the likelihood of a voltage sag occurring and information describing the sensitivity of important loads within the facility [28].

A. Synchronous Generators

Synchronous generators comprise of rotating inertia due to their rotating parts. These generators are capable of injecting the kinetic potential energy preserved in their rotating parts to the power grid in case of disturbances or sudden changes. The system is robust against instability [29]. The load demand of this machine may vary dramatically and irregularly due to the stochastic load characteristics. The rapid and frequent changes of load may result in serious voltage and frequency fluctuations phenomena [7]. In addition, the generator starting can draw several times of their full load current which may result in the significant voltage sags and cause the magnetic contactors to drop out and disrupt sensitive equipment. Voltage sag may cause the apparatus tripping, shutdown commercial, domestic and industrial equipment of drive system [10].

The starting current of a large synchronous machine before synchronization is typically 6-12 times the rated current when line started. The voltage drop caused by this starting current is the same in the three phases causing balanced voltage sag. The voltage drops suddenly and recovers gradually as the machine reaches its rated speed [14]. The number of loads affected by voltage sags depends on the source impedance. If a synchronous machine is subjected to instantaneous voltage sag, high torque peaks are developed that may pull machine out of step or damage the machine shaft or equipment connected to the shaft. To inhibit these conditions, protection equipment will disconnect the machine from supply [19].

If a short circuit is applied at the terminal of a synchronous generator, the current will start out very high and decay to a steady-state value. In a synchronous generator the field current is supplied by an external DC source. This external source will continue to supply voltage to the field windings of the generator [16]. The prime mover continues to drive the rotor that produces the required induced voltage in the stator winding which in turn supplies a continuous fault current. The steady state short-circuit current value will persist unless interrupted by a switching device such as a circuit breaker. As short circuit current continues flowing in the circuit, the generator impedance increases due to the increase in winding temperature [8].

A cross-sectional view of a three phase non-salient, two-pole synchronous generator is illustrated in Figure 1 [6]. The synchronous generator consists of three phase stator windings symmetrically distributed around the air-gap. The rotor field is produced by applying a DC current to the rotor field windings and a rotating field is produced in the air-gap which is also known as the excitation field [22]. The induced voltages in the armature windings have the same magnitudes but they are 120 electrical degrees apart. To obtain the synchronous generator mathematical model, the rotor reference frame is identified. The rotor windings are distributed symmetrically with respect to the orthogonal axes. To have a steady torque, the rotating fields of the stator and rotor must have equal speed called synchronous speed [24].

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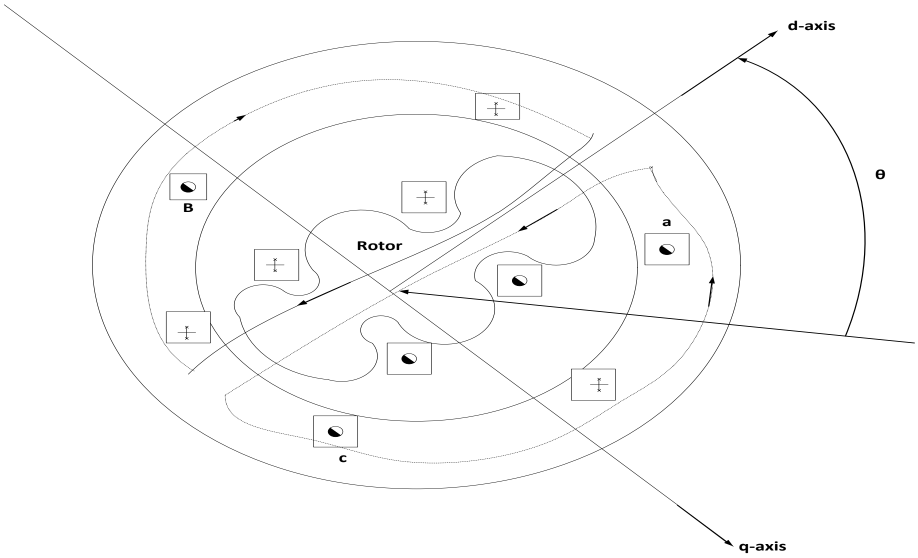

Figure 1: Cross-sectional view of a two-pole, salient pole synchronous generator

This speed of a synchronous generator is calculated as [25]:

$$n_s = \frac{120f}{p} = \frac{60\omega_s}{\pi p} \qquad 1$$

Where f is the frequency in Hz, $\omega_s = 2\pi f$ is the angular frequency in rad/s, p is the number of poles and n_s is the synchronous speed in rpm.

B. Solution to the Voltage Sags Problem

Voltage sag can be reduced through the following [2], [23]:

i. Synchronous Motor Starting: When a motor is switched on, there is a high inrush current from the mains which may cause a drop in voltage likely to affect receptor operation. To overcome this, some sector rules prohibit the use of motors with direct on-line starting systems beyond a given power.

ii. Reducing the Number of Faults: Limiting the number of faults is an effective way to reduce voltage sags. Fault prevention actions may include tree trimming policies, the addition of lightning arresters, insulator washing and the addition of animal guards.

iii. Reducing the Fault-Clearing Time: Reducing the fault-clearing time leads to less severe voltage sags. This does not affect the number of events but their durations. The modern static circuit breakers are able to clear the fault well within a half cycle at the power frequency, thus ensuring that no voltage sag can last longer.

iv. System Design and Configuration: Many actions in distribution system design can be employed for mitigating voltage sag. A certain improvement can be recorded by installing current-limiting reactors or fuses in all the other feeders originating from the same bus as the sensitive load.

C. Classification of Voltage Sags

Voltage sags are classified into seven types, based on fault type and load connection. In each type, the magnitude of phase voltages and angle, are different [27]. Figure 2shows the phasor diagrams of different types of voltage sags. Types A is symmetrical voltage sag while type B, C, D, E, F, and G are unsymmetrical voltage sags and their coefficients affect the torque pulsations of synchronous generator during and after the sag [4], [23].

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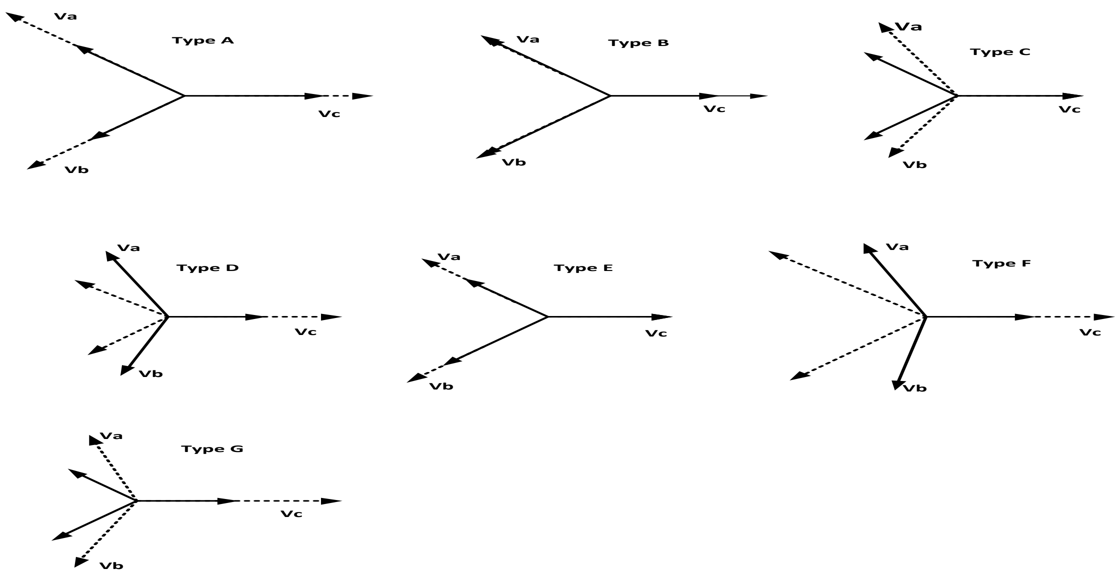

Figure 2: Voltage sag categories

II. MATERIALS AND METHOD

Sag duration and magnitude affect the generator responses. In this paper for simplicity purposes, it is assumed that magnetization and hysteresis effects are negligible. Although voltage sags can be either symmetrical or asymmetrical but only the effect of sag duration and magnitude on synchronous generator are analyzed in this paper. A Stochastic prediction method for voltage sag estimation using fault positioning method is used. This is based on assuming fault positions distributed throughout the network, with each position representing a location of faults in a particular part of the network as depicted in Figure 3 which consist of two generators with a transmission line between them.

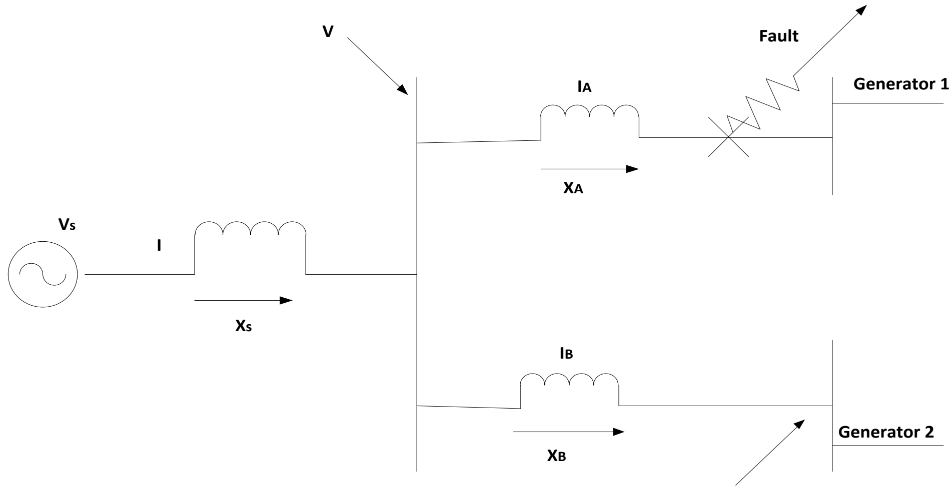

Figure 3: Network for voltage sag calculation

From Figure 3, the current flow through the network is given as:

$$I = I_A + I_B \qquad 2$$

In normal condition, that is, without fault in the network

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$I = \frac{V}{X_A + Z_A} + \frac{V}{X_B + Z_B}$ 3

$V = I\left(\frac{1}{X_A + Z_A} + \frac{1}{X_B + Z_B}\right)$ at $3.5\ (\text{Sec}) < t < 1\ (min)$ 4

When a fault occurs in generator 1, because of short circuit, a high current will flow through the generator1 as well as source current I. During this time, voltage in generator 2 is decreased due to increase of voltage drop across source reactance X_S, this causes voltage sag.

$I = \frac{V}{X_A} + \frac{V}{X_B + Z_B}$ 5

$V_{Sag} = V_s - IX_s(1 - s)$ 6

$\%V_{Sag} = \frac{V_{Sag}}{V_{Total\ \ Sag}} \times 100$ at $0.05 < s < 0.9$ 7

During the fault condition, voltage drop (IX_s) increases and hence voltage sag decreases from its nominal value.

Where, Z_A is the impedance of generator 1, Z_B is the impedance of generator 2, X_S is the source reactance, X_A is the reactance of generator 1, X_B is the reactance of generator 2, I is the current from supply source, I_A is the current in generator 1, I_B is the current in generator 2, V_s is the voltage from supply source and Sis the voltage sag magnitude, T is the sag duration.

III. SIMULATION

In order to observe the effect of the sag on the generator performance, a 4150 kVA synchronous generator is modeled based on different range of voltage sags duration and magnitude using computer simulation. The generator system is connected to the power source of 161kV to supply the power demand to the generator. The generator parameters and rated quantities are depicted in Table I. The two generators units have the same p.u. values.

Under normal condition current flow to the generator that can withstand voltage variation through feeder A and to the generator that cannot withstand voltage variation through feeder B. When there's fault on feeder A, a high current will flow to feeder A and currents flow to feeder B will reduce, consequently, voltage will drop in feeder B. This voltage drop is known as voltage sag. During voltage sag, load torque and excitation voltage are assumed to be constant.

Table 1: Rated data of the synchronous generator parameters and rated quantities

Quantity	Value
Speed	1800 r/min
Inertia	960 Kgm^2
Voltage line-line	10.5 kV
Apparent power	4150 kVA
Current	228 A
Power factor	0.9
Pole pairs	2
Stray Resistance	0.11 Ω
Transformer Reactance	2.59 Ω
Inductance d	151mH
Inductance q	75 mH

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IV. DISCUSSION OF RESULT

To assess the ability of the approaches for sag effect on the performance analysis of synchronous generator, a simulated system was investigated. The computed simulation results are presented in Figures 4 to 6.

Figure 4 shows the variation between the generator supply voltages with sag duration during normal condition. The voltages remain constant because the connected generator system is working under the normal conditions and the simulation is run at no fault or voltage sag.

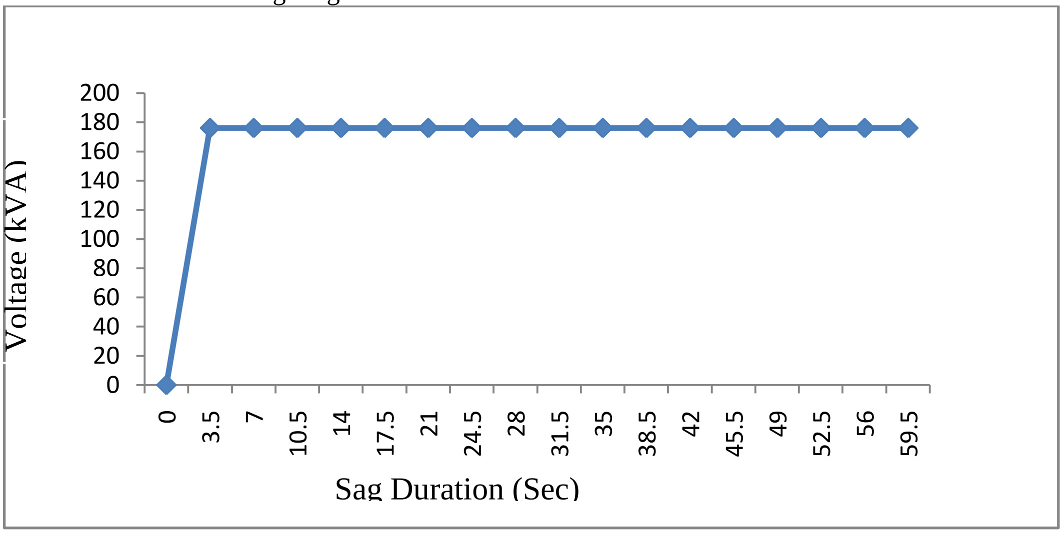

Figure 4: Voltage versus sag duration under normal condition

Figure 5 shows the variation between the percentage voltage sag with sag duration during voltage sag condition. At sag duration of 3.5 sec, sag begins by changing generator terminal voltages.

Figure 6 shows the relationship between the percentage voltage sag with voltage sag magnitude during voltage sag condition.By using the fault positioning method, voltage sag is introduced in the generator bus voltage from 0.05 to 0.90. The test shows that the generator failed at 0.35and at 0.40 due to a voltage decrease of 97%. A fault occurs at the load terminal and this affects the damped torque pulsation of the synchronous generator with supply power frequency.

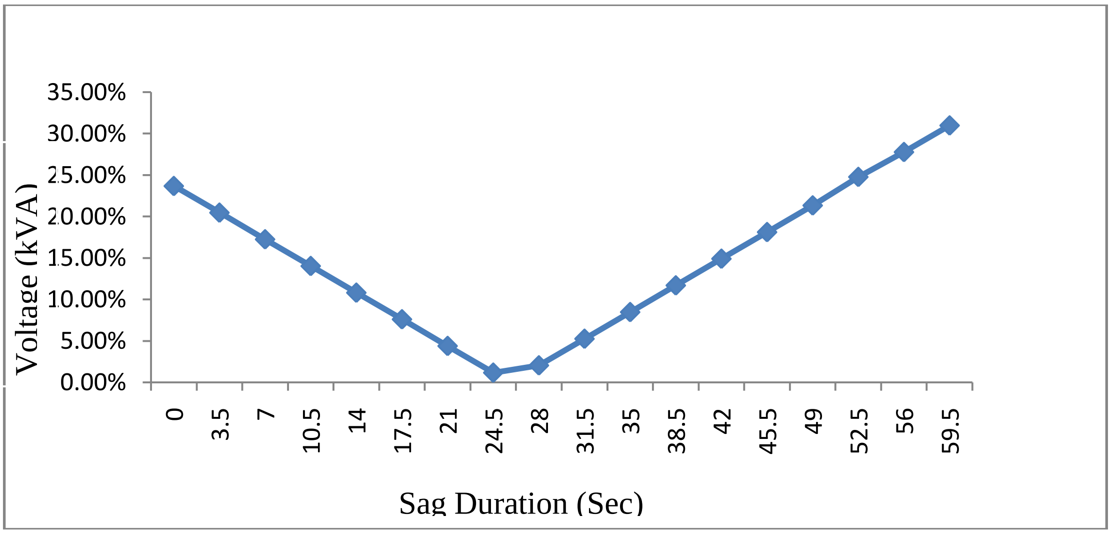

Figure 5: Percentage voltage sag versus sag duration

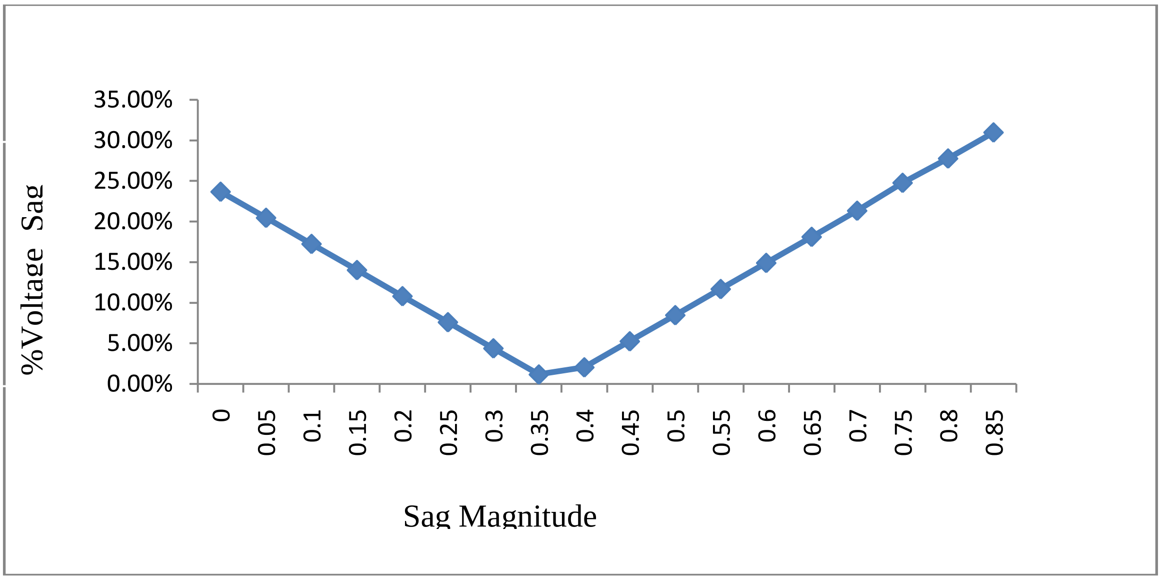

Figure 6: Percentage voltage sag versus sag magnitude

IV. CONCLUSION

The effects of voltage sags on the performance of synchronous generator have been presented with different sag durations and magnitudes. The effectiveness of the method used depends upon the rating of sag magnitude, sag duration and percentage voltages sag. In the test system it is observed that after a particular amount of voltage sag, the voltage level at the load terminal decreases. The results indicate that the faults generated at the load terminal by the sag have more intensive effect on the synchronous generator torque pulsations.

The result of this research paper provides the cost effective solution to mitigate voltage sag by establishing the appropriate voltage quality level, required by the generator.

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