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Utilizing MATLAB-SIMULINK Based Technique for Teaching the Voltage Sag/Swell Mitigation Using DVR to Graduate Students

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ABSTRACT

Voltage sag which is reduction in rms voltage for a short duration could be caused by short circuits, the connection of overloads to system and starting of large motors. The interest to study the voltage sags is mainly because of the problems which they cause on several types of power system equipment: adjustable-speed drives, process-control equipment, and computers are notorious for their sensitivity. In this research description and definition of voltage sag and swell and their destroyer effects on power system is presented. Also the effect of voltage sag/swell mitigation using dynamic voltage restorer (DVR) is investigated. Due to educational purpose of this paper to teaching compensation advantages to graduate students the well-known software MATLAB-SIMULINK has been employed to simulate and investigate the effects of voltage sag/swell mitigation.

Keywords: *MATLAB-SIMULINK software, voltage sag/swell, educational purpose, dynamic voltage restorer*

1. INTRODUCTION

Voltage sags and swells in the low and medium voltage distribution system have been considered to be the most frequent type of power quality problems based on recent power quality researches. Their effect on sensitive loads is severe. Their effects could be ranged from the disruptions of load to influential economic losses up to millions of dollars. Several solutions have been proposed to protect sensitive loads against this kind of disturbances but the dynamic voltage restorer is considered to be the most effective solution. The advantage of this custom power device includes its dynamic response to the disturbance, lower cost and smaller size. As shown in Fig.1 the voltage sags may be occurred at any instant of time, with amplitudes ranging from 10 to 90% and a duration which lasting between a half cycle to one minute [1]. On the other hand, voltage swell, is defined as an increase in rms voltage or current for 110% to 180% under power frequency for duration between 0.5 cycles to 1 minute. Energizing a large capacitor bank or switching off a large inductive load is a typical system event which causes swells [2].

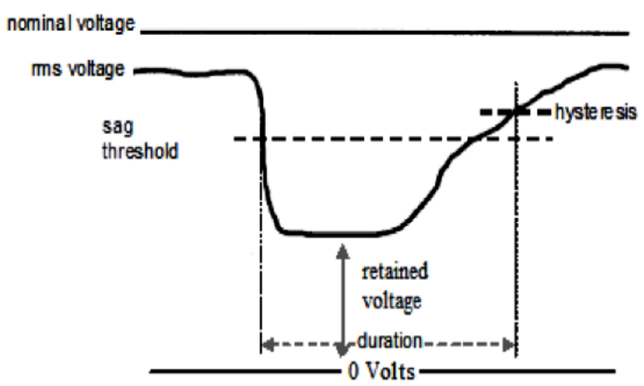

Fig.1.Voltage sag wave

2. VOLTAGE SAG/SWELL MODUL

This module consists of 5 weeks theoretical course was held in *Borujerd Branch of Islamic Azad University*. The most important contents of this module includes of sag/swell principles and its difference with other power quality phenomena. The voltage sag/swell effects on power system are introduced, analyzed and finally the method of voltage sag/swell compensation and elimination based implementation of dynamic voltage restorer are investigated. It also covers some examples in this area. The aim of this module is to introduce a helpful method to instructor for teaching the examples of voltage sag/swell distortions, its effects on power system and its mitigation and compensation with their results. Therefore, the author of this article has been using MATLAB-SIMULINK as an instructional tool to teach this subject. This method of instruction has enabled students to understand the voltage sag/swell concept and the necessity of sag/swell elimination and compensation subject.

The success rate of students in understanding the subject shows the ability of this method.

An essential feature of using MATLAB-SIMULINK is to incorporate the visualization and control of results in a graphical form on a computer screen. This is particularly important in the analysis or simulation of power networks because of their large size and wide geographical distribution.

In order to better describe of voltage sag/swell concepts, at first five questions as follows are presented:

- What is voltage sag/swell?
- What are the main creating factors of voltage sag/swell?
- What are the effects of voltage sag/swell on power system?

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- What is method of voltage sag/swell compensation?
- What is the performance of dynamic voltage restorer in voltage sag/swell compensation?

It is important to understand the difference between an interruption and voltage sag. An interruption is defined as a complete loss of voltage whereas when the voltage drops below 90% of nominal it said that sag is occurred. Interruptions occur when a source-side protective device cuts a section of the circuit due to a fault condition. The interruption may be sustained or momentary. Sustained interruptions continue minutes or hours whereas commentaries last a few seconds. The voltage sag lasts only as long as it takes the protective device to clear the over-current condition, typically up to ten cycles. The range in seconds then is roughly 0.001 to 0.167 seconds (about the range of a blink of an eye). A person can in many cases see the lights blink during these events. System wide, an urban customer on average may see 1 or 2 interruptions a year whereas the same customer may experience over 20 sags a year depending on how many circuits are fed from the substation. Why are there more sags than interruptions? Since the most substations have several transformers and also multiple circuits per transformer, when a fault occurs at a circuit, the supply voltage is depressed and therefore affecting many circuits not just the one where the fault occurs. Depending on the transmission system stiffness, other substation banks and even other substations may be influenced. In addition, many breakers operate multiple times clearing the same fault.

This voltages sag and swell have these disadvantages [3-5]:

- Voltage sag and swell can cause sensitive equipment (such as found in semiconductor or chemical plants) to fail, or shutdown.
- Voltage sag and swell can create a large current unbalance that could blow fuses or trip breakers.

3. CREATING FACTORS OF VOLTAGE SAG

3.1 Short circuit faults

Among symmetrical and unsymmetrical short circuits, the effect of three phase short circuit is more sever on the voltage sag [4, 6]. In order to evaluate the amount of the voltage sag in the radial distribution system, the voltage divider model can be used as illustrated in Fig. 2.

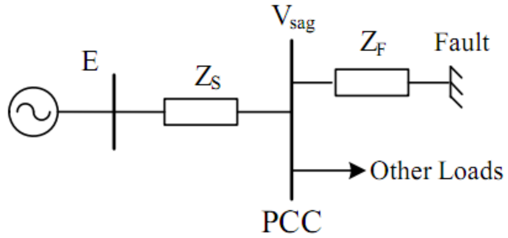

Fig.2.Voltage divider model for computing voltage sag in a radial distribution system

In this figure, impedance Z_s indicates the source impedance at the point of common coupling (PCC) and Z_F is the impedance between the PCC and fault point. The voltage at PCC bus can be determined as follows [7]:

$$V_{Sag} = \frac{Z_F}{Z_S + Z_F} E \qquad (1)$$

In versus of short circuit capacity of system at fault point and PCC, the magnitude of voltage sag can be determined as follows:

$$V_{Sag} = 1 - \frac{S_{FLT}}{S_{PCC}} \qquad (2)$$

Single phase or two phases are most short circuits in power systems. In that case, it is needed to take all three phases into account or use the symmetrical component theory. For non-symmetrical faults the voltage divider in Fig.2 can still be employed but it must be split into its three components including a positive-sequence network, a negative sequence network and a zero-sequence network.

For a single-phase fault, the voltage sag in faulted phase is calculated as follows [8]:

$$V_{sag} = \left| \frac{(Z_{F1} + Z_{F2} + Z_{F0})}{(Z_{S1} + Z_{S2} + Z_{S0}) + (Z_{F1} + Z_{F2} + Z_{F0})} \right| \qquad (3)$$

Where Z_{S1}, Z_{S2} and Z_{S0} are the source impedance values and Z_{F1}, Z_{F2}, and Z_{F0} the feeder impedance values in the three components.

For a phase to phase fault, the voltage sag in two faulted phases is calculated as follows:

$$V_{sag} = \left| \frac{(Z_{F1} + Z_{F2})}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})} (a^2 - a) \right| \qquad (4)$$

3.2. Starting of the induction motors

Another important factor that affects voltage sag is the large induction motor start-up [8]. During start-up of an induction motor the starting current is around 5 to 6 times that of current in the normal operation. To describe and explain the start-up phenomenon, the schematic diagram during the induction motor start-up is illustrated in Fig. 3. In the figure, Z_S is the source impedance and Z_M is the motor impedance during the start-up period.

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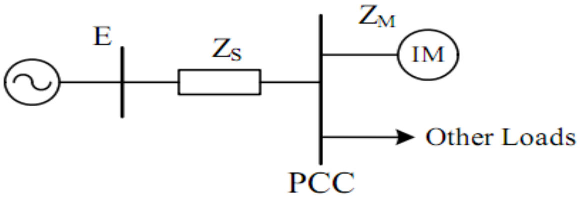

Fig.3.The equivalent circuit of the induction motor for the study of voltage sag

The created voltage sag in the bus which supplies the motor and other loads can be determined as follows [9]:

$$V_{Sag} = \frac{Z_M}{Z_S + Z_M} \qquad (5)$$

When a motor of rated power S_{motor} is fed from a source with short-circuit power S_{source}, we can write for the source impedance:

$$V_{Sag} = \frac{S_{source}}{S_{source} + \beta \times S_{motor}} \qquad (6)$$

Where, β is the ratio between the starting current and the nominal current.

In case which the voltage during motor starting is too low, in order to connect the equipments to the same bus, one can decide to utilize a dedicated transformer. This leads to the network shown in Fig.4.

Let again Z_S be the source impedance at the PCC, Z_M the motor impedance during start-up period, and Z_T the transformer impedance. The magnitude of the voltage sag experienced by the sensitive load is:

$$V_{Sag} = \frac{Z_T + Z_M}{Z_S + Z_T + Z_M} \qquad (7)$$

Like before with introducing the short circuit power of the source with S_{source}, the rated power of the motor with S_{motor} and supposing that the transformer has rated power of the motor and impedance ε, with assuming $\beta = 6$ we get from [10]:

$$V_{Sag} = \frac{(1+6\varepsilon)S_{source}}{(1+6\varepsilon)S_{source} + 6S_{motor}} \qquad (8)$$

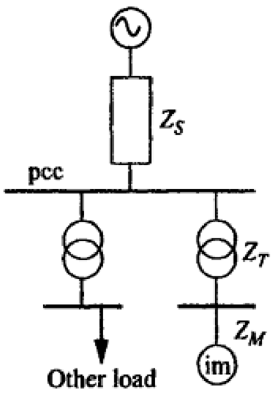

Fig.4. Induction motor starting with dedicated transformer for the sensitive load.

4. FACTORS AFFECTING SAG CHARACTERISTICS

Many factors affect the sag characteristics which are mentioned as follows:

A) Type of fault: The first factor which affects sag characteristic is type of fault in the power system. Depending whether the fault type is symmetrical and unsymmetrical, sag will be balanced or unbalanced in all three phases. Also the magnitude and phase angle of sag will depend on the type of fault [11].

B) Location of fault: The location of fault in the system has a great impact on the magnitude and phase-angle jump of the sag beside with the type of fault. The sensitive load is at distribution level but the faults at distribution as well as at hundreds of kilo-meters distance away at the transmission level will have an influence on the magnitude and phase-angle of the sag [12].

C) X/R ratio of the lines: The X/R ratio of fault to source impedance is under changing with the X/R ratio of the line which will affect the magnitude as well as phase-angle jump [12]. In order to study the effect, the X/R ratio of one of the lines could be changed and the magnitude and the phase angle jump of voltage at PCC can be analyzed.

D) Point on wave of sag initiation: The point on wave of sag initiation is defined as the phase angle of the fundamental voltage wave at which the voltage sag starts.This angle is corresponded to the angle at which the short circuit occurs. Since the most faults are associated with a flashover, they are more likely to occur near the voltage maximum rather than near the voltage zero. Upward crossing of the fundamental voltage is an obvious choice for reference to quantify the point of wave initiation [11]. Phase-angle jump will change more as compared to the magnitude of sag with change in point on wave of sag initiation.

E) Point Single/Double circuit transmission: Double circuit transmission in the power system is a common technique to improve reliability. Another interesting analysis on studying the influence of disconnection of lines on the sag magnitude and phase angle can be carried out by keeping any the transmission line as a double circuit. Compared with single circuit configuration of the same line, the results show that with changes in the transmission configuration, it affects the X/R ratio of impedances, which will affect the characteristic of sag.

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5. VOLTAGE SAG/SWELL COMPENSATION USING DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer is a static device which works by adding the 'missing' voltage during voltage sag. Basically this means that the device injects voltage into the system in order to bring the voltage back up to the level required by the load. Using switching system coupled with a transformer which is connected in series with the load the injection of voltage is obtained. Two types of DVRs are available; those without and with energy storage. DVRs equipped with energy storage use the stored energy to modify and correct the voltage waveform whereas devices without energy storage have this capability to correct the voltage waveform by drawing additional current from the supply. The difference between a DVR with energy storage unit and a UPS is that the DVR only supplies the part of the waveform which has been missed due to the voltage sag, not the whole waveform. Another difference between DVRs and UPS is that dynamic voltage restorer generally cannot operate during interruptions. A schematic of a DVR is presented in Fig.5. As can be seen the basic structure of DVR consists of an injection/booster transformer, a voltage source converter (VSC), a harmonic filter and a control system.

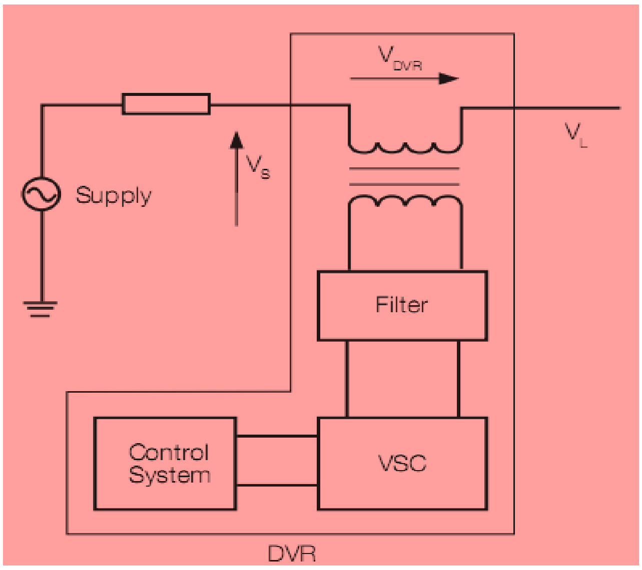

Fig.5. Basic compensation principle of shunt active power filter

It is mentioned in [11] that the dynamic voltage restorer is the best economic solution for voltage sag compensation based on its capabilities and its small size. In the case of systems without storage, none of the inherent issues with storage are relevant. DVRs can be used for purposes other than just voltage sag mitigation which this is other advantages of these systems. These added features include power factor correction, harmonic compensation and limiting the fault current.

6. DISCUSSION AND SIMULATION

The specifications of test system considered in this research to teaching graduate students and to illustrate the disadvantages of voltage sag and corresponding effects on power system equipment and also familiar to voltage /swell compensation is presented as follows.

Suppose that a 5 MVA motor is started froma100MVA, 11 kV supply. The starting current is six times the nominal current. This is a rather large motor for a supply of this strength, as we will see soon. The voltage at the motor terminals during motor starting can be estimated as:

$$V_{Sag} = \frac{S_{source}}{S_{source} + \beta \times S_{motor}} = \frac{100}{100 + 6 \times 5} = 0.77 = 77\%$$

Consider a dedicated supply for the motor in the previous example. The motor is fed through a 5 MVA, 5% 33/11kV transformer from a 300MVA, 33kVsupply. Note that the fault current at the 33kV bus is identical to the fault current at the 11kV in the previous example. That gives the following parameter values: S_{source} = 300MVA, S_{mator} =5 MVA, and € = 0.05, giving, a sag magnitude as follows:

$$V_{Sag} = \frac{(1+6\varepsilon)S_{source}}{(1+6\varepsilon)S_{source} + 6S_{motor}} = \frac{(1+6\times 0.05)\times 300}{(1+6\times 0.05)\times 300 + 6\times 50} = 0.93 = 93\%$$

Note that the reduction in sag magnitude is mainly due to the increased fault level at the PCC, not so much due to the transformer impedance. Neglecting the transformer impedance (€ = 0), gives voltage sag as follows:

$$V_{Sag} = \frac{(1+6\times 0.0)\times 300}{(1+6\times 0.00)\times 300 + 6\times 5} = 0.91 = 91\%$$

Assume that a single phase fault occurs on one of the 132 kV feeders. The 132 kV system is solidly grounded, therefore the positive and zero sequence source impedances are similar. For the feeders, the zero sequence impedance is about twice the positive and negative sequence impedance. Positive sequence impedance is assumed to be equal with negative sequence impedance.

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$$Z_{S1} = Z_{S2} = 0.09 + j2.86\%$$
$$Z_{S0} = 0.047 + j2.75\%$$
$$Z_{F1} = Z_{F2} = 0.101 + j0.257\% / lm$$
$$Z_{F0} = 0.23 + j0.65\% / km$$

The voltage sag for a three phase fault at 20 km of PCC is determined as follows:

$$V_{Sag} = \frac{Z_F}{Z_S + Z_F} = \frac{(0.101 + j0.257) \times 20}{(0.09 + j2.86) + (0.101 + j0.257) \times 20} = 0.667\angle -6.68$$

The voltage sag of faulted phase for a single line to ground fault at 20 km of PCC is determined as follows:

$$Z_F = Z_{F1} + Z_{F2} + Z_{F0} = [2(0.101 + j0.257) + (0.23 + j0.65)] \times 20 = 8.64 + j23.28$$
$$Z_S = Z_{S1} + Z_{S2} + Z_{S0} = [2(0.09 + j2.86) + (0.047 + j2.75)] = 2.977 + j5.72$$
$$V_{Sag} = \frac{Z_F}{Z_S + Z_F} = \frac{(8.64 + j23.28)}{(2.977 + j5.72) + (8.64 + j23.28)} = 0.798\angle +1.47$$

The voltage sag of faulted phases for a line to line fault at 20 km of PCC is analyzed as follows.

If the load is connected in delta, the equipment terminal voltages are the phase-to-phase voltages and could be calculated as follows:

$$Z_F = Z_{F1} + Z_{F2} = 2(0.101 + j0.257) = 0.202 + j0.514$$

$$Z_S = Z_{S1} + Z_{S2} = 2(0.09 + j2.86) = 0.18 + j5.72$$

$$V_{sag} = \frac{(0.202 + j0.514) \times 20}{(0.18 + j5.72) \times 20 + (0.202 + j0.514) \times 20}(1\angle 240 - 1\angle 120) = 0.153\angle -107.94$$

7. SIMULATIONS AND RESULTS

In this section the influence of dynamic voltage restorer on voltage sag is analyzed. As shown in Fig.6 the MATLAB-SIMULINK simulation tool was used to develop a model that allowed the simulation and testing the theory calculations, which were implemented in the controller of the dynamic voltage restorer.

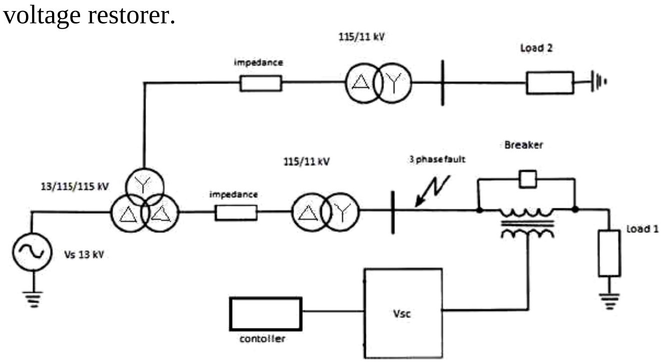

Fig.6. Test system

The MATLAB-SIMULINK based simulation of test system in presence of dynamic voltage restorer is shown in Fig.7.

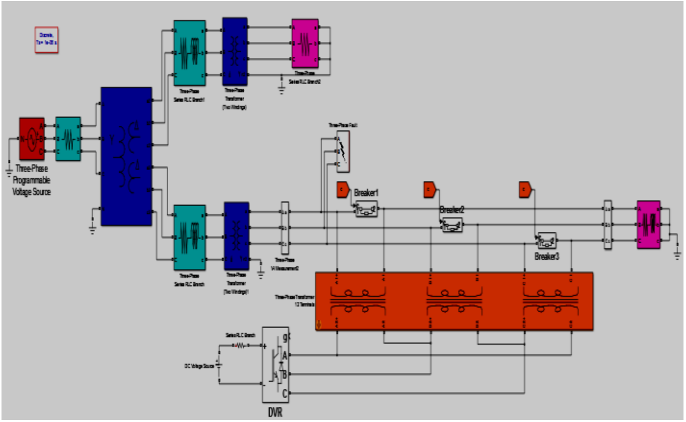

Fig.7.The voltage sag analysis of test system in presence of DVR with SPWM switching technique under short circuit

The setting of the parameters of dynamic voltage restorer in MATLAB-SIMULINK environment is shown in Fig.8.

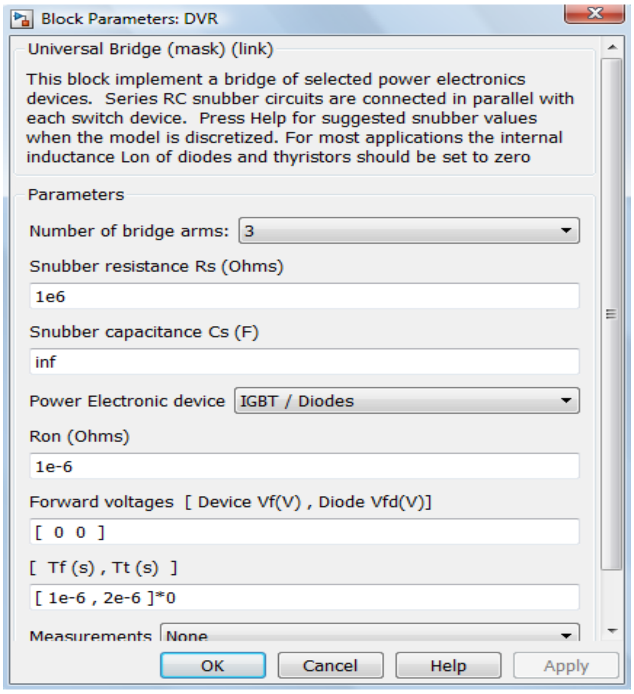

Fig.8. the setting parameters of DVR

In this paper, the SPWM switching technique for dynamic voltage restorer is implemented which is shown in Fig.9.

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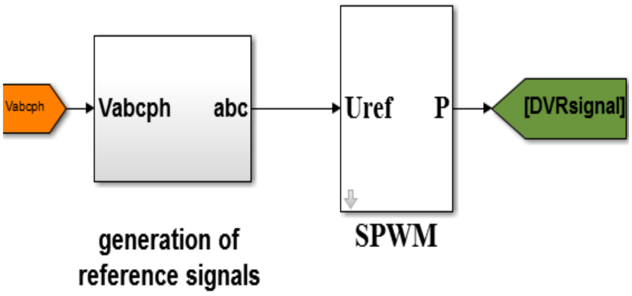

Fig.9.SPWM switching technique

The subsystem of RMS measurement for evaluating the rms value of voltage sag or swell under dynamic voltage restorer operation with and without fault is shown in Fig.10.

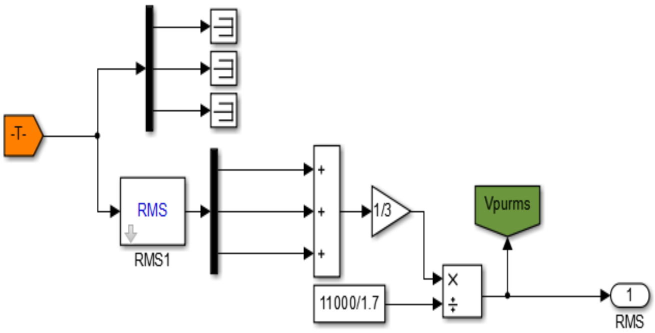

Fig.10.The rms monument block

The instantaneous voltage sag and corresponding rms value from simulation results without presence of DVR are shown in Figs.11 and 12.

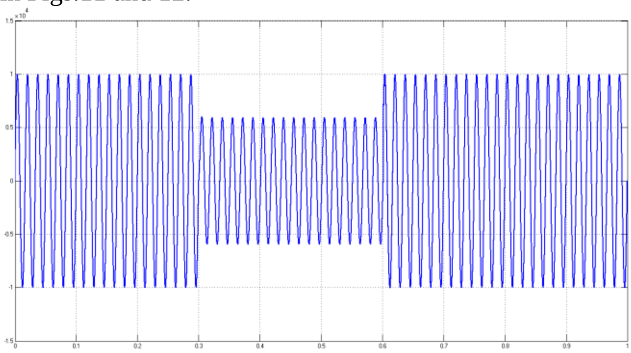

Fig.11.The instantaneous voltage sag without compensator

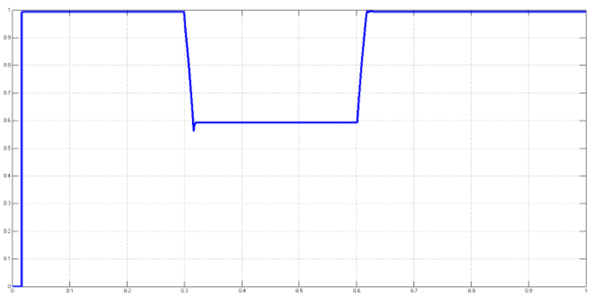

Fig.12.The rms value of voltage sag without compensator

The instantaneous voltage sag and corresponding rms value from simulation results with presence of DVR are shown in Figs.13 and 14.

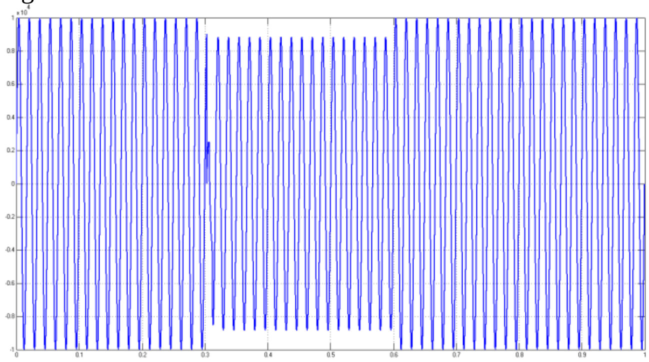

Fig.13.The instantaneous voltage sag with dynamic voltage restorer

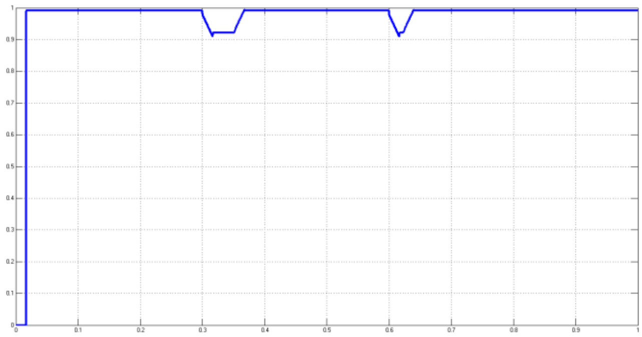

Fig.14.The instantaneous voltage sag with dynamic voltage restorer

The instantaneous voltage swell and corresponding rms value from simulation results without presence of DVR are shown in Figs.15 and 16.

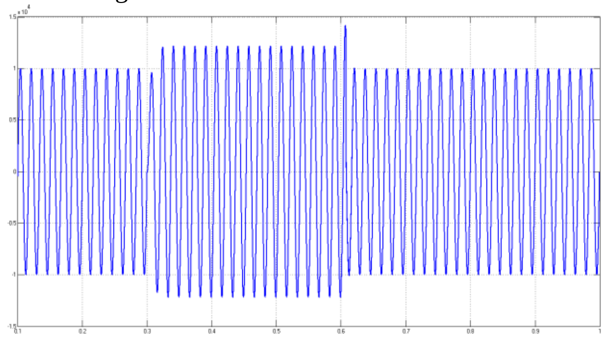

Fig.15.The instantaneous of swell voltage without dynamic voltage restorer

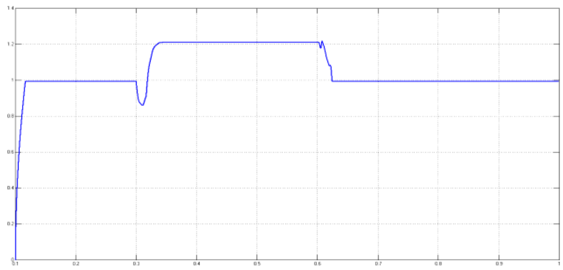

Fig.16.The instantaneous of swell voltage without dynamic voltage restorer

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The rms voltage of compensated voltage swell with presence of DVR is shown in Fig.17.

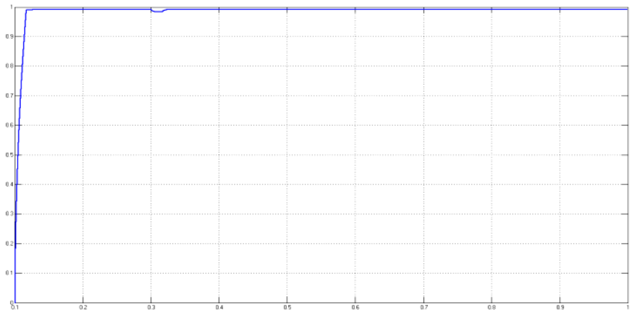

Fig.17.The instantaneous of swell voltage with dynamic voltage restorer

8. STUDENTS FEEDBACK

The methodology illustrated in this paper has explained for 30 senior graduate students in power system, all of them have passed power quality courses. The students employ the methodology and in the presence of instructor filled a questionnaire form. The questionnaire, comprising six questions, is listed in Table 1.

Table 1: Questionnaire Answered by the Students and Engineers

Question	Score
1. The content of this practical is valuable for a student of engineering course	
2. Are you understanding the concept of voltage sag/swell and its difference with other power quality phenomena	
3. Are you more familiar with the creating factors of voltage sag and swell in power system	
4. Are you more familiar with the influence of starting of induction motors on voltage sag in PCC	
5. Are you more familiar with the influence of voltage sag/swell on system	
6. Are you more familiar with the performance of dynamic voltage restorer in sag/swell compensation	

The students graded them as 1(poor), 2 (medium), 3 (good), and 4 (excellent).

Table 2 gives the average scores for each question out of students' feedback.

Table 2 Average Score Obtained From Students' Answers

	Average Score
Question 1	3.52
Question 2	3.75
Question 3	4.00
Question 4	3.12
Question 5	3.82
Question 6	3.34
Total	3.53

9. CONCLUSION

Present article has outlined and illustrated a MATLAB-SIMULINK model to illustrate the creating factors of voltage sag/swell and investigate the effect of this phenomenon on power system. The improvement of power system condition is proportional to compensation duration by dynamic voltage restorer. The method considerably reduces the time and cost needed to teach the subject. Therefore, it is very useful for educational purposes and useful preparatory exercises for student to learn the subject. The evaluation of the project involving more than 30 students indicates benefits of this project in teaching the subject.

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