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DVR and D-STATCOM Mitigation Techniques of Power Quality Effects on Induction Motors

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Abstract: Power quality disturbances have always been a major concern among engineers. Any slight variation in voltage amplitude or frequency can cause customer equipment to fail, at a substantial cost in time and money. In this project we will use some mitigation techniques to protect the induction motor from excessive temperature (additional losses and high currents) and the rotor vibration torque pulsation caused by power quality disturbances. These mitigation techniques reduce the effects of the power quality disturbances on the induction motor, where the simulations done using MATLAB/SIMULINK.

Keywords: Power quality, mitigation, induction motor, D-STATCOM, DVR.

1. INTRODUCTION

In recent years, the demand for electricity goes on increasing which in turn leads to the need for dynamic and complex electric power system with the utilization of renewable energy sources. In this increasing complex system, the Electric power quality (PQ), the fitness of electric power to consumers has become the great concern of customers, utilities, manufacturers, etc. The internal, external faults in the power system and usage of many power electronic devices greatly affect the power quality. There are two types of faults such as symmetrical and unsymmetrical faults usually occur in the power system that causes the power quality issues [1]. In addition to these faults, usage of motor loads, switching of loads, etc. in industries causes PQ problems [2-3].

Power quality problems in the power system have gained importance since the late 1980s. Power Quality (PQ) is related to the three parties concerned with the electric power: the utility companies, equipment manufacturers and electric power consumers. Understanding power quality can be confusing at best. There have been numerous articles and books concerning power quality [4]. Most of the equipment that is manufactured also distorts the voltage [5] on the distribution system, leading to what is known as poor power quality. As a result, it affects other equipment that was designed with the expectation of consistent undistorted voltage, and are thus sensitive to power disturbances resulting in reduced performance and will cause equipment miss operation or premature failure [6]. The cost of power quality problems can be very high and include the cost of downtimes, loss of customer confidence and, in some cases, equipment damage. Indeed, power quality is an important point in the relationship between suppliers and consumers [5] but might become a contractual obligation that stresses on improving voltage quality, availability, performance [7] and efficiency and these improvements will have benefits for industrial customers (customized and flexible availability) and for suppliers utilities [8].

Power quality is defined in the IEEE 100 Authoritative Dictionary of IEEE Standard Terms as The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment Utilities may want to define power quality as reliability [9]. From the Power Quality market or industry perspective, it is any product or service that is supplied to users or utilities to measure, treat, remedy, educate engineers or prevent Power Quality issues, problems and related items [10-12].

Modern industrial processes are based a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances and thus industrial loads become less tolerant to power quality problems. The power quality issues arise from the usage of modern devices such as voltage sag, voltage swell, harmonics, flicker, interruption, etc.. These issues greatly affect the system performance that may lead to system loss, safety, and economic problems and in some cases; it may result in

system failure. Therefore, there is a need for an accurate and reliable monitoring and control of power system. Monitoring of power system provides us information about power flow and demand and helps to identify the causes and location of power system disturbances before they cause interruptions or disturbances [13-14].

There exist many techniques using power electronics to mitigate these disturbances which are: Voltage Source Converters, Dynamic Voltage Restorer, Static Compensator, Distribution Static Compensator, Motor-Generator Set, Static Series Compensator, Low-Pass Filter, Passive Filter and Active Filter [15-18].

In this work the Dynamic Voltage Restorer and Distribution Static Compensator techniques are used to reduce the effect of over- under voltage and unbalanced voltage problems on the induction motor.

2. POWER QUALITY DISTURBANCES

Definition of power quality disturbances

There are different types of power quality disturbances and also different ways to define and categorize them. One possible categorization of power quality disturbances is the IEEE standard 1159-1995 which gives an excellent graphical definition of the various power quality problems (fig. 1) [19].

Fig. 1 Voltage Reduction Standard of IEEE Std. 1159-1995. [1]

Long-Duration Voltage Variations

This category includes disturbances with a large spectrum of possible durations, including very long durations, and with less clear definitions than those in the coming categories. Generally *Under-voltages*, *Over-voltages*.

A. Over-voltages

An *over voltage* is an increase in the RMS ac voltage greater than 110 percent at the rated supply line power frequency for a period of more than one minute [20]. It can be found by taking the

root mean square (r m s) value of the voltage over multiple of one half-cycle of the power system frequency as expressed in the following formula [21].

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{K=1}^N V^2(K\Delta t)} \quad (1)$$

Where $K\Delta t = t$

There are many causes of over voltage in the electric power distribution system. The overloading of distribution system, energizing capacitor bank, and switching of large size loads mostly causes the over voltage in the low voltage distribution networks. For example, switching off a large load and system switching operations like Switching on a large capacitor bank [22]. Overvoltage can be dangerous to both equipment and human. Electronic devices may experience immediate failure during the overvoltage conditions; however, transformers, cable, bus, switchgear, and rotating machinery (induction motor) do not generally show immediate failure.

B. Under-voltage

The *under voltage* in the electric power distribution system is the decrease in the value of ac RMS voltage to 90 percent at a power frequency for more than one minute duration [20]. Under-voltages can be the result of load switching, for example, switching on a large load and system switching operations like switching on a large inductor. These last until voltage regulation equipment on the system can bring the voltage back to normal. Overloaded circuits can also lead to under-voltages. Sometimes faulty connections or wiring and Loose or corroded connections can also cause under-voltages.

Under-voltages can cause equipment to fail. Motor controllers can drop out during under-voltage conditions. The dropout voltage of motor controllers is typically 70 – 80% of nominal voltage. Long duration under-voltages cause an increased heating loss in induction motors due to increased motor current. Speed changes are possible for induction machinery during under-voltage conditions [23].

C. Interruptions

If supply voltage decreases below a specified limit of 0.1 per unit for time duration of more than one minute, the event is known as an interruption. Control malfunction, equipment failure, and power system faults are few out of many reasons which cause the interruptions. These interruptions are also known as outages. Interruptions may be instantaneous, momentary, temporary and sustained. Duration range for different types of interruptions is as follow [23].

- 1) Instantaneous: 0.5 to 30 cycles
- 2) Momentary: 30 cycles to 2 seconds
- 3) Temporary: 2 seconds to 2 minutes
- 4) Sustained: greater than 2 minutes

The interruptions are usually caused by construction or maintenance in the power system. Temporary interruptions are usually caused by faults and are generally unpredictable and random occurrences. Momentary and temporary interruptions will almost always cause equipment to stop operating, and may cause breakdown of induction motor contactors. In some cases, interruptions may damage electronic soft-start equipment.

Short Duration Voltage Variations

The variation of the RMS voltage from nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to 60 seconds is called short duration variation.

Short Duration Voltage power outages account for 92% of power quality problems encountered by industrial customers [21]. The various types of Short Duration Voltage Variations can be divided into the two categories, sags and swell.

A. Voltage Sags (dips)

A *voltage dip (sag)* is a reduction in the voltage at a point in the electrical system below a threshold, followed by a voltage recovery after a short period of time. The voltage dip threshold is different to the interruption threshold and, in particular, it is assumed to be equal to 90% of the

declared voltage by EN 50160–2000 and IEC 61000-2-8–2002 and equal to 90% of the nominal voltage by IEEE 1159–1995. In IEEE 1159–1995 the term ‘sag’ is used instead of the IEC term ‘dip’; this recommendation distinguishes between instantaneous (from 0.5 cycles to 30 cycles), momentary (from 30 cycles to 3 seconds) and temporary (from 3 seconds to 1 minute) sags. We note that in IEEE 1159–1995, those voltages characterized by a magnitude between 80% and 90% of the nominal voltage with duration greater than 1 minute are classified as *undervoltages* [23].

The voltage sag in per unit of nominal system voltage is calculated as follow [23]:

$$V(pu)_{sag} = \frac{V(pu) * KVA_{sc}}{KVA_{LR} + KVA_{sc}} \quad (2)$$

Where,

$V(pu)$ = Actual system voltage, in per unit nominal

KVA_{LR} = Motor locked rotor kVA

KVA_{sc} = System short-circuit kV

Voltage sags are generally caused by faults (short circuits) on the system. Overloads can be another cause although it can be termed as being an under-voltage phenomenon or a voltage step. The other cause of sags is that caused when large motors start. Motors have the undesirable effect of drawing several times their full load current while starting. For example, an induction motor will draw six to ten times its full load current.

The sag magnitude simply indicates the severity of the sag, and duration is the time the sag is maintained for. Sensitive equipment such as Adjustable Speed Drives (ASDs), control equipment, and computers are very sensitive to sags. Sags caused by faults are the ones which cause the majority of equipment trips.

B. Voltage Swell

A *voltage swell* is an increase in RMS voltage or current to between 0.1 and 0.9 p.u. at the power frequency for duration between 0.5 cycles and 1 minute. [20] The common sources of swell are high impedance neutral connection, sudden load reduction and a single phase fault on a three phase system.

The origin of swells is single line ground failures, upstream failures, switching off a large load or switching on a large capacitor. But voltage swell are much less common than voltage sags. For example, faults on one line cause voltage rise on other phases.

Since swells usually last for a short period, there is no significant impact on equipment. However, light bulbs can burn out and safety problems may arise and may cause breakdown of components on the power supplies of the equipment, though the effect may be gradual, accumulative effect. The increase in output from incandescent lighting may be noticeable if the duration is longer than three minutes.

C. Voltage unbalance

Voltage unbalance (also called *voltage imbalance*) is sometimes defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent [20]. Figure 1.9 shows a three-phase voltage waveform where the phases a, b, and c have different amplitudes [24].

This imbalance can be caused by different loads on the phases, resulting indifferent voltage drops through the phase-line impedances.

A voltage imbalance can cause a reverse-rotating air gap field in induction machines, increasing heat loss and temperature rise. The voltage unbalance in percent is defined by the National Electrical Manufacturers Association (NEMA) in Standards Publication No. MG 1-1993 as [25]:

$$Unbalance (\%) = \frac{\text{Maximum Deviation from Average}}{\text{Average of Three Phase - to - Phase Voltages}} \times 100 \quad (3)$$

The adverse effects of unbalanced voltages on induction motors stem from the fact that the unbalanced voltage breaks down into two opposing components that can be described using the method of symmetrical components. Through the use of symmetrical components, an unbalanced

three-phase system of voltage or current phases can be described using three balanced systems of phases termed positive, negative and zero sequence. However, in the case of machines, the zero sequence components will be zero since motors are typically connected delta or ungrounded wye and thus there is no path to neutral for zero sequence components to flow. Completely balanced systems would contain only positive sequence components of voltage, current and impedance.

D. Harmonic Distortion

Harmonics are a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency [19]. These harmonics interact with the fundamental frequency waveform and each other to produce a distorted waveform which can cause significant damage to power system components. The magnitudes of the harmonics and their phase shifts determine the shape of the resulting waveform.

Harmonics distortion exists due to the nonlinear characteristics of the devices and loads on the power system. These devices are modelled as current sources that inject harmonic currents into the power system. Voltage distortion results as these currents cause nonlinear voltages across the system impedance. Harmonic distortion is of growing concern for many customers and for the overall power system due to increasing application of power electronics equipment [22].

Harmonics distortion levels are characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion (THD) and total demand distortion (TDD) [22].

The total Harmonic distortion (THD) is defined as [22]:

$$THD_{\% \text{ of fundamental}} = \frac{V_T}{V_1} \times 100 = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100 \quad (4)$$

Where: V_n is the rms value of the harmonic component.

V_1 is the rms value of the fundamental component. The effect that harmonics have on electrical equipment, in particular sensitive electronic equipment, has only become apparent in the last number of years [26]. Harmonic current injection from customer loads into the utility supply system can cause harmonic voltage distortion to appear on the utility system supply voltage. This harmonic current and voltage distortion can cause overheating of rotating equipment, increase in transformer winding temperature which reduces the efficiency and the life span, and current-carrying conductors.

3. Mitigation Methods for Power Quality Disturbances

The focus of this section is on mitigation devices rather than mitigation through the design of the power system and the production facilities and loads connected to it. Most newly developed mitigation devices use power electronics [27].

Voltage Source Converters (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage.

The VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics.

Dynamic Voltage Restorer (DVR)

A DVR, Dynamic Voltage Restorer is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder and in synchronism with the voltages of the distribution system. By injecting voltages of controllable amplitude, phase angle, and frequency (harmonic) into the distribution feeder in instantaneous real

time via a series-injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is significantly out of specification for sensitive load equipment. It is designed to mitigate voltage sags and swells on lines feeding sensitive equipment [28].

A viable alternative to uninterruptible power systems (UPS) and other utilization solutions to the voltage sag problem, the DVR is specially designed for large loads of the order of 2 MVA to 10 MVA served at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS. DVR can also be used to mitigate troublesome harmonic voltages on the distribution network [28].

DVR comprises of three main parts:

1. Inverter
2. DC energy storage
3. Control system

The basic configuration of a DVR is shown in Fig.2;

Fig.2 Basic configuration of a DVR

Static Compensator (STATCOM)

The STATCOM (or D-STATCOM when applied to the distribution system) is the common name for a shunt connected, force-commutated, PWM-controlled VSC mounting IGBTs, possibly with an energy storage device behind it; shown in Fig. 3. STATCOM is an abbreviation for static synchronous compensator. The PWM-control provides a fast response and makes the STATCOM suitable for mitigating fast disturbances such as voltage dips as well as flicker. These devices can generate and consume reactive power and an interesting feature is that they can also control the active power if the VSC is equipped with an energy storage device [29].

Fig. 3 Basic building blocks of the STATCOM

Distribution Static Compensator (D-STATCOM)

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Fig. 4, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power;
2. Correction of power factor; and
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter. The basic configuration of the D-STATCOM is shown in the diagram below;

Fig. 4 Configuration of a D-STATCOM

Motor-Generator Set (M-G Set)

The principle of a motor-generator set (M-G set) is that a motor powered by the supply is driving a generator powering the load (see Fig. 5). Between the motor and the generator, on the same axis, are flywheels which can store and release rotational energy to compensate for voltage drops in the supply. The inertia of the flywheels keeps the load voltage steady even if the supply voltage drops, providing a so called ride-through time. This is the time the load can continue normal operation during a voltage dip or an interruption [30].

Disadvantages of the M-G set include sometimes high noise levels and maintenance requirements, as well as the relatively large size of the equipment. Also, there are losses in all three machines and, because the ride-through depends on inertia, the frequency and voltage will drop continuously during ride-through [30].

There are ways of alleviating the latter of the disadvantages. Special types of M-G sets use a so called written-pole motor instead of the generator in the set. This machine is a special synchronous generator which can produce constant 50 Hz-frequency power even as the machine slows. The polarity of the rotor's field poles is continually changed, changing the number of poles of the machine with each revolution. While the revolutions per minute are held above a certain value (by the flywheels' inertia) the power frequency will remain constant. This increases the ride-through time. Another way of compensating the voltage and frequency drops is by adding a rectifier followed by an inverter to the output of the generator [30].

Fig.5 Block diagram of a typical M-G set with flywheel

Static Series Compensator (SSC)

In the static series compensator, an energy storage device is connected in series with the feeding line through a VSC. The voltage injected from the SSC is added to the supply voltage to keep the load voltage stable as it is shown in Fig. 6 [31].

Fig. 6 Diagram of a SSC system.

4. Effect of Over-Under and unbalanced voltages on Induction Motor without Mitigation:

Power quality problems like *Under-voltages*, *Over-voltages* and *unbalanced*, are major concern of the industrial and commercial electrical consumers due to enormous loss in terms of time and money. Today, new technologies known as Custom Power, using power electronics-based concepts, have been developed to provide protection from power quality problems. This section studies the mitigation techniques on induction motor performances, which are the Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) techniques.

Simulation of the DVR and D-STATCOM are implemented in MATLAB/SIMULINK software. Simulation shows the use of DVR and D-STATCOM to improve the induction motor torque, speed and currents. The disturbances are created on input voltage of induction motor, for duration of 1 minute. The results simulation for each effect is shown in the following figures.

Fig. 7 Rotor speed with under-voltage

Fig. 8 Electromagnetic torque with under-voltage

Fig. 9 Rotor speed With Over-voltage

Fig. 10 Electromagnetic torque with Over-voltage

Fig. 11 Rotor speed With Unbalanced

Fig. 12 Electromagnetic torque with Unbalanced

Dynamic Voltage Restorer, (DVR) Techniques:

The DVR consists of an Injection transformer, a Voltage Source Converter (VSC), Energy Storage Unit and a Control and Protection unit as shown in Fig. 13.

Fig. 13 Schematic Diagram of DVR Configuration

Energy Storage Unit in DVR can be external batteries or capacitors charged from the supply line feeder through a rectifier. The purpose of energy storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages.

A Voltage Source Converter is a power electronic system capable of generating a sinusoidal voltage at any required frequency, magnitude, and phase angle. DVR configurations use the VSC to generate the voltage required to compensate for the voltage disturbance events. Since the majority of the under-over voltages observed on distribution systems is unbalanced, the VSC will often be required to operate with unbalanced switching functions for the three phases and must therefore be able to treat each phase independently. The output voltage of the inverter is varied by using different PWM schemes available.

Injection transformers are responsible for connecting the DVR to the sensitive loads (Induction Motor) in the distribution network via the high tension windings and transforming and coupling of the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection transformer also serves the purpose of isolating the load from the system (VSC and control mechanism). Generally three single-phase transformers are used as injection transformers for injecting the compensating voltages to the system at the load bus.

The control unit of DVR is only responsible for controlling the compensating voltage generation by controlling the PWM pulses to the gates of semiconductor switches of the VSC.

Modeling and simulation:

The performance of the DVR with the induction Motor is analyzed using MATLAB/SIMULINK program simulation software. The DVR is connected in series between a three phase programmable (controllable) voltage source with 400V line to line RMS voltage, 50 Hz and a load Induction Motor with power 4.5 HP (4KW), and voltage 400V, 50 Hz, 1430 RPM. The Simulink model is shown in Fig. 14.

Fig. 16 voltage V_{rms} with DVR

Fig. 18 Rotor speed with DVR

Fig. 19 Electromagnetic torque with DVR

A three phase Over voltage is simulated by increasing the voltage of each phase to 160% of the normal value for a duration of 1 minute from $t=0.25\text{sec}$. Fig. 20 shows the Vrms (stator voltage) without DVR while Fig. 21 is the Vrms (stator voltage) with DVR. The Rotor speed and Electromagnetic torque of the motor with DVR are displayed in Fig. 22 and Fig. 23, respectively. The overall simulation time was 1.5minute.

Fig. 20 voltage Vrms without DVR

Fig. 21 voltage Vrms with DVR

Fig. 22 rotor speed with DVR

Fig. 23 Electromagnetic torque with DVR

C. Three phase unbalanced voltages

In this case, the unbalanced voltage is created by unbalanced resistive and inductive (RL) circuit. The inductors of the RL load are not equal in each phase. The resistor is 10Ω in each phase, and the inductors are 30 mH, 10 mH, and 10 mH, respectively. The voltage is 110% of the

normal value for duration of 1 minute start from $t=0.15$ sec. and the voltage unbalance factor is 4.54%. The simulation duration was 1.5 minute. Fig. 24 and Fig. 25 display the V_{rms} (stator voltage) without DVR and the three phase voltage unbalanced (stator voltage) without DVR.

Fig. 24 voltage V_{rms} without DVR

Fig. 25 three phase voltage unbalanced without DVR

The solution is done using DVR, and the following figures show the simulation results. Fig. 26 is V_{rms} (stator voltage) with DVR and Fig. 27 the stator voltage for three phase with DVR. Rotor speed and Electromagnetic torque of induction motor with DVR are displayed in Fig. 28 and Fig. 29, respectively.

Fig. 26 voltage V_{rms} with DVR

Fig. 27 voltage for three phase with DVR.

Fig. 28 Rotor speed of motor with DVR

Fig. 29 Electromagnetic torque with DVR

Distribution Static Compensator (D-STATCOM) Techniques:

The D-STATCOM consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer.

The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM

and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power. Fig. 30 shows a basic configuration diagram of the D-STATCOM.

Fig. 30 Configuration Diagram of D-STATCOM.

Modeling and simulation

The performance of the D-STATCOM in Induction Motor load is evaluated by using MATLAB/SIMULINK program as simulation software. The model system comprises a 230kV, 50Hz transmission system, feeding into the primary side of a 3-winding transformer connected in Y/Y/Y, 230/11/11 kV, the induction motor load with power 4.5 HP (4KW), and voltage 400 V, 50 Hz, 1430 RPM is connected to Δ/Y transformer 11kV/400V, and it connected to the 11 kV, secondary side of the first transformer. A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load point. A 750 μ F capacitor on the dc side provides the D-STATCOM energy storage capabilities. To show the effectiveness of this controller in providing continuous voltage regulation, simulations were carried out with and with no D-STATCOM connected to the system. The SIMULINK model is shown in Fig. 31.

Fig. 31 SIMULINK model of the D-STATCOM with IM load

Simulation results

In order to assess the operation of the D-STATCOM system, the results are obtained by simulating in MATLAB/SIMULINK software. The performance of the system has been considered in minimum operation time is one minute duration. The figures of all our simulation is shown for specific period (i.e.in the specific event that is created)

A. Under-voltages

The under-voltage is created by the three line to ground fault, without the D-STATCOM. The line to line voltage on each phase is reduced by 80% with respect to the reference voltage. The duration time is 1 minute start from $t=0.35$ sec. The simulation duration was 1.5 minute. The results of simulation have been shown in the following figure.

Fig. 32 voltage Vrms without D-STATCOM

Similarly, a new set of simulations was carried out but now with the D-STATCOM connected to the system, where the very effective voltage regulation provided by the DSTATCOM can be clearly appreciated. The results are shown in the following Figures.

Fig. 33 voltage Vrms with D-STATCOM

Fig. 34 Rotor speed with D-STATCOM

Fig. 35 Electromagnetic torque with D-STATCOM

B. Over-voltage

The first simulation contains no D-STATCOM and three phase capacitive load applied at all phases, to create three phase Over voltage for a duration of 1 minute, starting from $t=0.25\text{sec}$. The Over-voltage at the load point is 118% with respect to the reference voltage. The results of simulation have been shown the voltage V_{rms} (stator voltage). The simulation time is 1.5 minutes.

Fig. 36 voltage V_{rms} without D-STATCOM

Similarly, a new set of simulations was carried out but now with the D-STATCOM connected to the system. The results as shown in the following Figures.

Fig. 37 voltage V_{rms} load with D-STATCOM

Fig. 38 Rotor speed with D-STATCOM.

Fig. 39 electromagnetic torque with D-STATCOM.

C. Three phases unbalanced

The unbalanced is created by a unbalanced resistive and inductive (RL) load, the inductors of the RL load are not equal in each phase, the load resistor is 10Ω in each phase, and the load

inductors are 30 mH, 10 mH, and 10 mH, respectively. The voltage is 75% of the normal value for duration of 1 minute start from $t=0.15$ sec. and the voltage unbalance factor is 7.05%. The simulation duration was one minute. Fig. 40 shows the V_{rms} (stator voltage) without D-STATCOM and Fig. 41 displays the three phase stator voltage unbalanced without D-STATCOM.

Fig. 40 voltage V_{rms} with D-STATCOM

Fig. 41 three Phase unbalanced voltages With D-STATCOM.

The following figures show the simulation results, of the solution using D-STATCOM.

Fig. 42 voltage V_{rms} with D-STATCOM

Fig. 43 Rotor speed of induction motor with D-STATCOM

Fig. 44 electromagnetic torque of IM with D-STATCOM.

Comparisons of Stator and Rotor currents: From the previous simulation of the disturbances, we measured the current Stator and Rotor of each phase, with and without mitigation. The evaluation results are given in the following tables.

Table 1: stator and rotor currents of IM with and without DVR.

Current	IRated	under voltage		Overvoltage		voltage unbalanced	
		no mitigation	DVR	no mitigation	DVR	no mitigation	DVR
I _{sa}	7.8	17.22	9.03	10.85	7.92	14.43	7.78
I _{sb}	7.8	14.18	9.39	13.03	6.69	14.57	6.98
I _{sc}	7.8	18.22	7.69	13.88	8.03	11.31	9.07
CUF stator(%)	--	14.26	11.64	13.79	11.35	15.82	12.12
I _{ra}	4.62	1.78	5.69	1.97	4.63	4.12	4.27
I _{rb}	4.61	1.92	6.67	2.51	5.55	5.63	4.51
I _{rc}	4.67	1.51	6.53	1.61	5.06	5.08	3.71
CUF rotor(%)	--	13.05	9.63	20.68	8.85	16.65	10.88

The results in the table show that the DVR mitigation technique reduces the stator CUF from 14.26 % to 11.64 % with Under-voltage disturbance. Where the rotor CUF reduced by 3.42 %. For the Over voltage, the stator CUF is decreased by 2.44 %, and the rotor CUF reduced by 11.83 %.

The stator CUF with Unbalanced voltage VUF= is 15.82% without DVR mitigation and it is 12.12 % after mitigation. The decrease of the rotor CUF is more important which is equal to 5.77%.

Table 2: stator and rotor currents of IM with and without D-STATCOM.

Current	I Rated	under voltage		Overvoltage		voltage unbalanced	
		no mitigation	D-STATCOM	no mitigation	D-STATCOM	no mitigation	D-STATCOM
I _{sa}	7.75	10.35	8.89	11.76	6.87	11.67	7.62
I _{sb}	7.75	12.27	7.72	12.2	7.78	9.21	8.33
I _{sc}	7.75	13.21	7.76	9.48	7.12	8.38	8.7
CUF stator(%)	--	13.34	4.96	14.95	5.32	14.08	7.261
I _{ra}	4.75	2.54	4.08	1.45	2.72	2.01	4.01
I _{rb}	4.82	1.86	4.72	1.78	3.01	1.45	3.67
I _{rc}	4.79	1.83	4.12	2.22	3.08	1.84	4.08
CUF motor (%)	--	11.87	5.26	20.18	7.37	17.92	6.37

The tabulated results show that the D-STATCOM mitigation technique reduces the stator CUF from 13.34 % to 4.96 % with Under-voltage disturbance, Where the rotor CUF reduced by 8.38%.

For the Over voltage, the stator CUF is reduced from 14.95% to 5.32%, and the rotor CUF reduced by 12.81 %. The stator CUF with Unbalanced voltage VUF=14.08% without D-STATCOM mitigation and it is 7.26% after mitigation. The decrease of the rotor CUF is more important which is equal to 11.55%.

5. Conclusion

Power quality has adverse effects on induction motor performances. The increase in current, torque ripple and temperature due to power quality disturbances affects the induction motor efficiency and life time. The use of mitigation techniques is important to reduce effects of power quality problems. The DVR and D-STATCOM mitigation methods have been used to minimize the effect of under-voltages, over-voltages and unbalanced voltages on the induction motor currents, torque ripple and rotor speed.

The results presented in this work show the effectiveness of the DVR technique in reducing the induction motor CUF, where the rotor CUF reduction is very important compared to that of the stator for the three disturbances. The torque ripple peak to peak decreases from 122.7 N.m to 72.3 N.m. The D-STATCOM technique is also used to mitigate the effects of Under-voltage, Over-voltage and Unbalanced voltage on the induction motor performances. The obtained results show the decrease of the CUFs and ripple torque. We conclude from the comparison of the two techniques, that the DVR mitigation method is faster than the D-STATCOM, but the D-STATCOM is more reliable.

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