Comparative Analysis of Multiple-pulse VSC-Based STATCOM's for Voltage-Dip Mitigation

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Abstract- This paper includes the performance of a Flexible Alternating Current Transmission Systems (FACTS) device, namely, STATic synchronous COMpensator (STATCOM) based on 6, 12, 24 and 48-pulse Voltage Source Converter (VSC), for the mitigation of voltage-dip caused by the starting of a high power induction motor. The different configuration of the STATCOM's implemented improves the voltage profile feeding to a high power induction motor at starting by injecting a controllable current to the supply line having an acceptable limit of harmonics as per the standards of IEEE. The capability of the STATCOM's to compensate the reactive power to the system when the voltage dip occurs due to starting of high power induction motor load is described. The 48-pulse VSC employed in the STATCOM injects an almost sinusoidal current of variable magnitude, in quadrature with the line voltage, thereby emulating an inductive or a capacitive reactance at the point of connection with the line and introduces a very less amount of harmonics in to the system. Author has developed all the multiple-pulse VSC-based STATCOM's and implemented it into a power-system consists a high power induction motor in MATLAB/Simulink environment to show the voltage-dip mitigation capability. The harmonic contents to be introduced by the different configurations of the STATCOM's are also shown by the author.

Index Terms- Static Synchronous Compensator (STATCOM), Voltage-dip mitigation, Voltage Source Converter (VSC), power quality, Voltage Injection Capability, Harmonics.

I. INTRODUCTION

In the past, equipment used to control industrial process was mechanical in nature, which was rather tolerant of voltage disturbances. Nowadays, modern industrial equipment typically uses a large amount of electronic components, such as program logic control (PLC), adjustable speed drives and optical devices, which can be very sensitive to the voltage disturbances. The majority of disturbances that cause problems for electronic equipments are voltage dip or voltage sags [1]-[2]. Voltage dips may cause tripping, production disturbances and equipment damages. The voltage dips are found especially troublesome because they are random events lasting only a few cycles. However, they are probably the most pressing power quality problem facing many industrial customers today [3]. The concern for mitigation of voltage dip has been gradually increasing due to the huge usage of sensitive electronic equipment in modern industries. The investigator has shown that when heavy loads are started, such as large induction motor drives, the starting current is typically 6 to 7 times of the full load current drawn by the motor. This high current cause dips in the voltage during starting intervals, because there is a lot of voltage drop across the distribution conductor as it is not designed for such heavy currents. Since the supply and the cabling of the installation are dimensioned for normal running current and the high initial current causes a voltage dip. Another reason for high starting current is the inertia of the load as high starting torque is required to start the high inertia loads, which is obtained by using high starting current. This problem becomes more severe at peak loading time. This is due to the fact that at peak loading time the voltage of the system is less than the rated voltage.

As the STATCOM is a solid-state voltage source converter coupled with a transformer, tied to a line can injects reactive current or power to the system to compensate the voltage-dip. The Voltage-Source Converter (VSC) is the main building block of the STATCOM. It produces square voltage waveforms as it switches the direct voltage source ON and OFF. The main objective of VSC is to produce a near sinusoidal AC voltage with minimum waveform distortion or excessive harmonic content as the lower order harmonics are very harmful for a machine [4]. The harmonic free voltage can be achieved by creating a number of pulses into a cycle [5]. To obtain the multiple-pulse converters i.e. 12- pulse, 24-pulse and 48-pulse VSC, two, four and eight, 6-pulse VSC's are used, with the specified phase shift between all converters. A 48-pulse VSC can be used for high power applications with low distortion, because it can ensure minimum power quality problems and reduced harmonic contents. A 12-pulse, 24-pulse and a 48-pulse GTO based VSC can be constructed using two 6-pulse, four 6-pulse, eight 6-pulse converter configurations by putting a phase-shift of 30° ,15° and 7.5° respectively. The STATCOM based on 48-pulse converter produces almost three phase sinusoidal voltage and maintains THD (Total Harmonic Distortion) well below 4%. [6] as per the comparison made by the author.

Srinivas K. V. et al in [7] developed a three-level 24-pulse STATCOM with a constant dc link voltage and pulse width control at fundamental frequency switching, validated the inductive and capacitive operations of the STATCOM with satisfactory performance. The harmonic content of the STATCOM current is found well below 5% as per IEEE standards. Sahoo A. K. et al in [8] developed a simulation model of 48-pulse VSC based STATCOM FACTS devices. This full model is validated for voltage stabilization, reactive power compensation and dynamic power flow control. It produces a sinusoidal AC voltage with minimal harmonic distortion from a DC voltage with variable loads.

Huang S. P. et al in [9] also investigated that the GTO based STATCOM consisting a 48-pulse three-level inverter regarding minimal harmonic distortion. It has fine dynamic response and can regulate transmission system voltage efficaciously.

II. THE STATCOM

The STATCOM is a VSC-based shunt device. It is made up of a voltage source converter (VSC), DC capacitor, shunt transformer and a controller associated with VSC as depicted in Fig.1. In general, STATCOM is capable of generating or absorbing independently controllable real and reactive power at its output terminals, when it is fed from an energy source or energy storage device at its input terminal. If there is no energy storage device coupled to the DC link and the losses are neglected, then shunt converter is capable of absorbing or generating reactive power only. Functionality, from the standpoint of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control. Like the mechanically powered machine, these converters can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source. Because of these similarities with a rotating synchronous generator, they are termed as: Static Synchronous Generator (SSG). When SSG is operated without an energy source and with appropriate controls to function as shunt-connected reactive compensator, it is termed, analogously to the rotating synchronous compensator (condenser) a Static Synchronous Compensator (STATCOM) or Static Synchronous Condenser (STATCON). Rotating synchronous condensers have been used in both distribution and transmission systems for 50 years. However, they are rarely used today because of a number of drawbacks as compared to the STATCOM.

A. OPERATING PRINCIPLE

A STATCOM is a controlled reactive-power source. It provides the desired reactive power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). The reactive power exchange of STATCOM with the AC system is controlled by regulating the output voltage amplitude of voltage source converter.

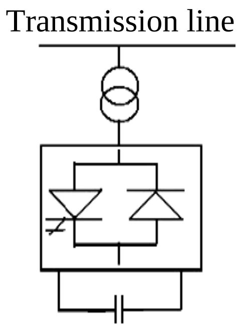


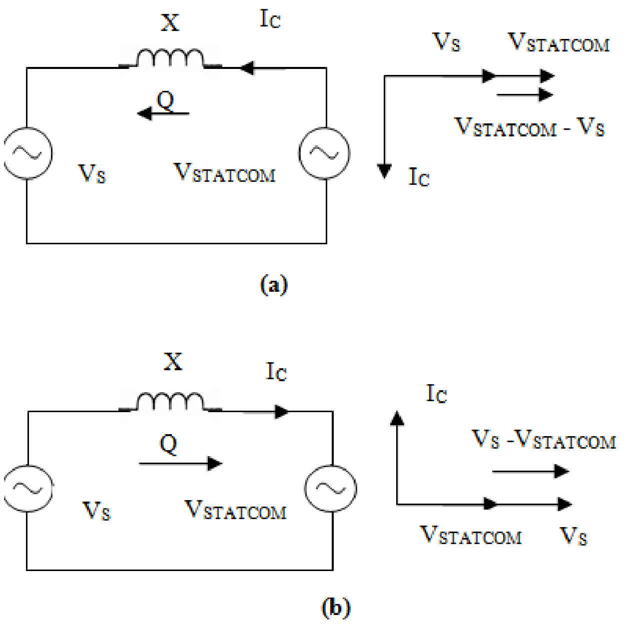
Fig.1. Voltage Source Converter based STATCOM

If the amplitude is increased above that of the AC system voltage, then the current flows from the STATCOM to the AC system and the device generates capacitive reactive power. If the amplitude is decreased to a level below that of the AC system, then the current flows from the AC system to STATCOM. The amount of type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. The reactive power supplied by the STATCOM is given by:

$$Q = \frac{V_{STATCOM} - V_S}{x} * V_S \qquad (2.1)$$

Where Q is the reactive power, $V_{STATCOM}$ is the magnitude of STATCOM output voltage, V_S is the magnitude of system voltage and X is the equivalent impedance between STATCOM and the system. When Q is positive the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system. The DC capacitor voltage controls the output voltage of voltage source converter. The output voltage of voltage source converter can be lead or lag with respect to AC system voltage by increased or decreased DC capacitor voltage respectively. When the voltage source converter voltage leads the bus voltage, the capacitor supplies real power to the system, acting as capacitive power source. On the other hand, when the voltage-source converter voltage lags the bus voltage, than the capacitor charged by consuming real power from the AC system having inductive reactance property, so that act as an equivalent inductor as illustrated by the phasor-diagrams shown in Fig. 2.

When the STATCOM output voltage ($V_{STATCOM}$) is lower than the system bus voltage (V_S), the STATCOM acts like an inductance absorbing reactive power from the system bus. When the STATCOM output voltage ($V_{STATCOM}$) is higher than the system bus voltage (V_S), the STATCOM acts like a capacitor generating reactive power to the system bus. In steady-state operation and due to inverter losses, the system bus voltage (V_S) always leads the converter ac voltage by a very small angle to supply the required small active power losses.



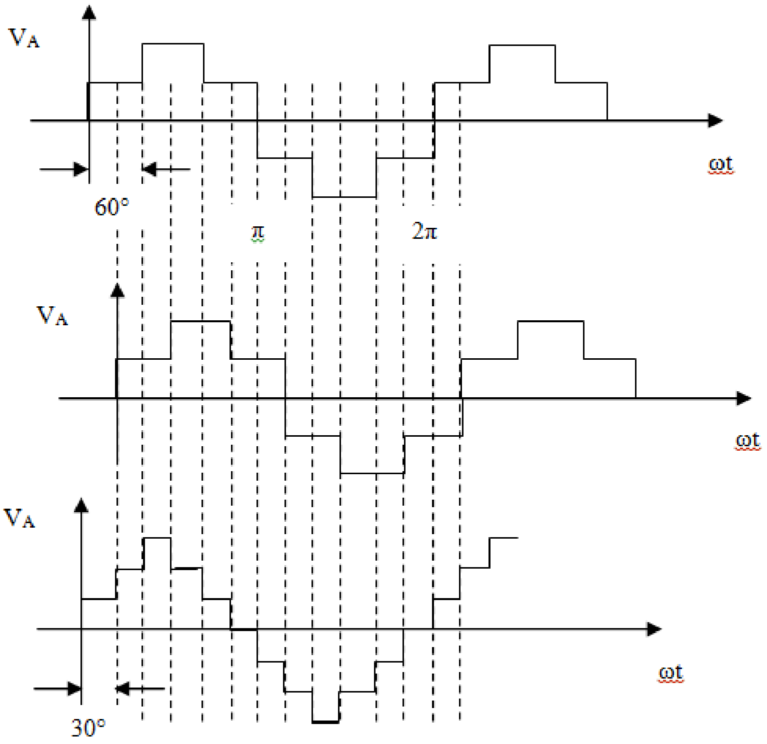


Fig. 2. STATCOM operation (a) Inductive operation (b) Capacitive operation

B. SIMULATION MODEL

The converter based technique (STATCOM) designed to mitigate the voltage-dip of the line caused by the induction motor is based on 6,12,24 and 48-pulse converter where the parameters have been calculated according to the line voltage and the rating of the motor under consideration. Further, the other configurations of the multiple-pulse converter i.e. 6-pulse, 12-pulse, and 24-pulse have been designed and employed in the STATCOM one by one. All the responses of the system after the implementation of the four different converter-based STATCOM have been studied. The study shows the effectiveness of the selected method. The complete design of the model made for simulation and implementation is as shown in Fig.3.

C. MULTIPLE PULSE GENERATION IN CONVERTER

As a multiple-step voltage is obtained in the converter by providing a phase shift between the converters circuits having a lesser number of steps. A 12-pulse or 12-step alternating voltage is achieved by 30° phase-shift between 6-pulse converter outputs. Every step of the 12-step voltage is of 30° as depicted in Fig.4. The phase-shift has been provided in the present work by using phase-shifting transformer.

Fig.4. Generation of 12-pulse by two 6-steps waveform

Hence, 12-pulses x 30° (each pulse) = 360° (a complete cycle) is readily obtained. The harmonic content in this alternating voltage are 12n±1; n=1, 2, 3 … along with the fundamental component as shown in eq.2.2 which is more sinusoidal as compared to conventional 6-pulse converter with less harmonic content.

$$v(t) = V_m \sin \omega t + \sum_{m=12n\mp1}^{\infty} \left(\frac{V_m}{m} V_m \sin m\omega t \right)$$

$$= V_m \sin \omega t + \frac{V_m}{11} V_m \sin 5\omega t + \frac{V_m}{13} V_m \sin 7\omega t + \frac{V_m}{23} V_m \sin 11\omega t + \ldots\ldots. \quad (2.2)$$

Finally, 24-pulse and 48-pulse converters are achieved by employing a phase-shift of 15° and 7.5° respectively between two 12-pulse converter configurations in the similar manner so that 24-pulses x 15° (each pulse) = 360° (a complete cycle) and 48-pulses x 7.5° (each pulse) = 360° (a complete cycle) are obtained. The firing sequences of the thyristors used are obtained according to the phase-shift and the number of pulses required. The firing sequence of the thyristor employed in the converter configuration can be get understand by the firing sequence of a conventional 6-pulse converter (T1T3T5-T4T6T2).

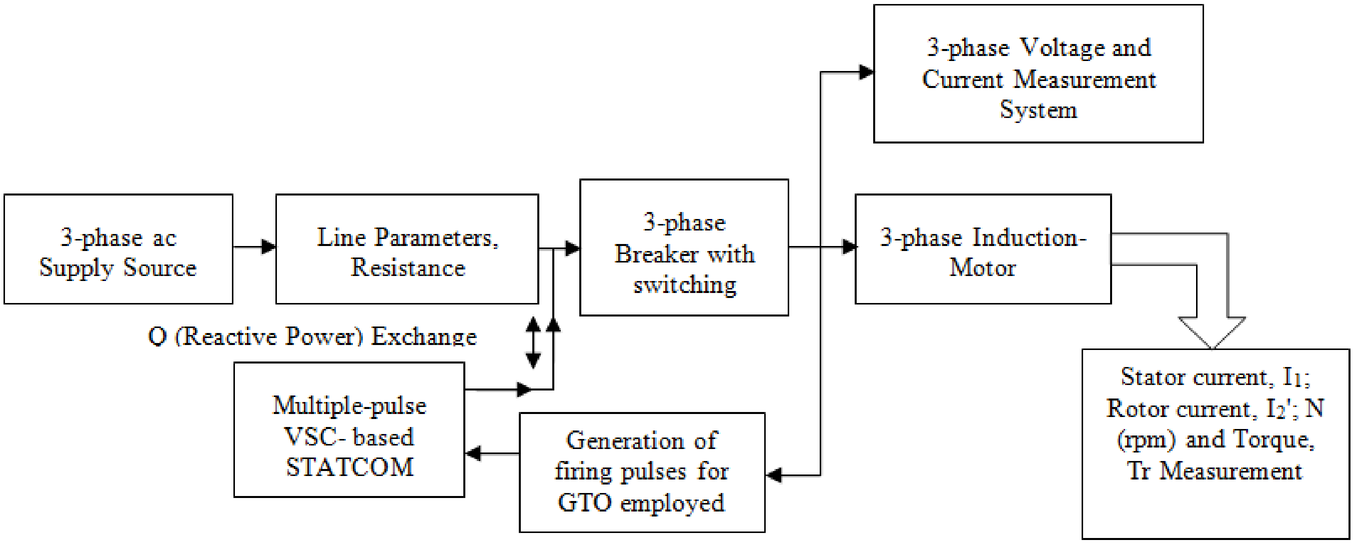
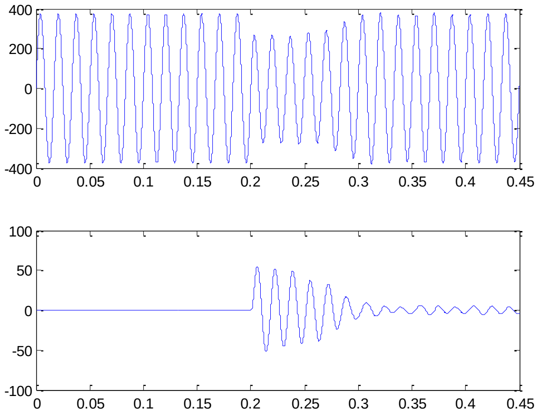


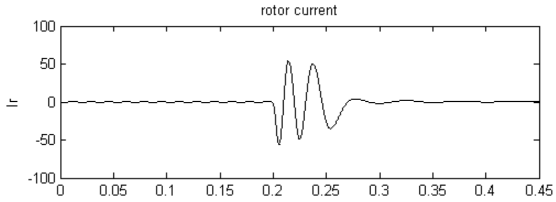
Fig.3 Design of the Multiple-Pulse VSC-based STATCOM

III. SIMULATION RESULTS

The complete model with the voltage-dip caused by the starting of a squirrel-cage induction motor of 100HP, 460V and 50 Hz is simulated first without STATCOM. A 3-phase breaker is chosen to start the induction motor and it is set to close at an instant t = 0.2 sec. The 3-phase voltage source with a small resistance in series with each phase is taken to implement a practical supply system. The measurement of the system voltage and supply current is provided by the 3-phase V-I measurement block and the stator current, rotor current, speed of rotor and electromagnetic torque are measured at bus-selector available in asynchronous-motor block. The system-voltage and current of all three phases during the motor-start at t = 0.2 sec and rotor current is as shown in Fig.5. The type of simulation used in *powergui* to simulate the problem is *continuous* with variable step-size and the solver chosen is ode23tb (stiff/TR-BDF2).



(a)



(b)

Fig.5 (a) System Voltage and Current during the Starting of the Motor and (b) Rotor Current

Simulation results show that a voltage dip of about 15-20% is introduces at the time of the starting of the induction motor and the motor drags a current of 5 to 6 times of the rated current as in fig.5(a). It is also depicted from the result that the rotor current is also 5 to 6 times of the rated current with lower frequency because of the introduction of the slip.

Now, the implementation of the STATCOMs consisting 6-pulse, 12-pulse, 24-pulse and 48-Pulse three-level converter has been made one by one with the model. The 48-pulse based STATCOM voltage and current delivered at load terminal during voltage dip are as shown in Fig.6 below. There is a minor difference in the capability of the voltage-dip mitigation by the different multiple-pulse STATCOMs but the content of the harmonics fed by the STATCOM voltage is very few in the case of 48-pulse configuration as in tabe.1.

The capacitors employed in the STATCOM act as a variable DC voltage source. Here, the capacitors modelled and simulated are initially charged (initial conditions) by the system voltage. The variable amplitude voltage produced by the inverter is synthesized from the variable DC voltage.

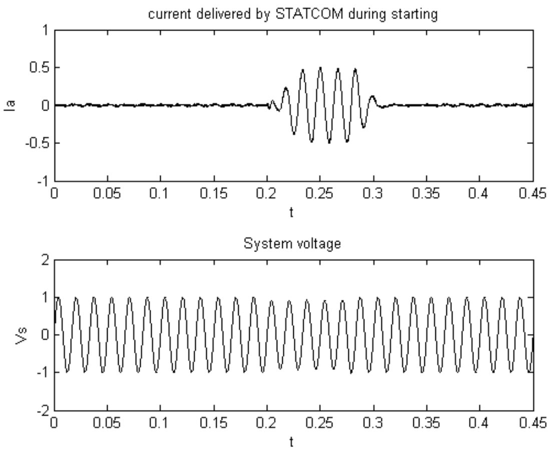


Fig. 6 STATCOM Voltage and Current Delivered during Voltage-Dip

As soon as the motor is started at t=0.2sec, the dip in the rms voltage introduced is mitigated well. A slight voltage-dip is there even after the implementation of the STATCOM. It is seen from the response that the current is lagging by an angle of 90° from system voltage i.e. a reactive power is fed to the system by the STATCOM during voltage-sag.

Table.1. Comparative Assessment of Multiple-Pulse STATCOMs for voltage-dip mitigation

S. No.	**Configuration of the STATCOM**	**Voltage-dip after mitigation**	**%Total Harmonic Distortion**
1.	6-pulse STATCOM	30.88%	4.34%
2.	12-pulse STATCOM	21.38%	4.49%
3.	24-pulse STATCOM	7.58%	4.64%
4.	48-pulse STATCOM	3.79%	4.95%

The FFT analysis of STATCOM's output clearly shows that the 48-pulses of a cycle of output voltage containing a fewer harmonics (THD = 3.79%) as compared to the other configurations.

IV. CONCLUSION

The results shows that whenever an induction motor is started, a voltage-dip of up to 25% is there in the system-voltage as shown in Fig.5 (a).Now, as soon as the multiple-pulse STATCOM is implemented into the system and comes under action, the voltage-dip, caused by the starting of the motor at t = 0.2sec onwards for 4-5 cycles, is mitigated well as the comparative results shows in table.1. above. A slight voltage-dip is found after the implementation of the STATCOM. The results also show that the voltage fed by the 48-pulse STATCOM adds a fewer harmonics into the system having THD = 3.79% which is within the accepted limit of IEEE standards.

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