Harmonics and Reactive Power Compensation of Three Phase Induction Motor Drive by Photovoltaic-based DSTATCOM

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ABSTRACT
As a result of rapid advancement in electrical and electronics technologies, the application of power electronics is growing day by day due to the significant advantages offered. But as a downside of the same, extreme application of power electronic-based converters has caused the excessive emission of harmonics as well as reactive power in power system networks. Due to the harmonics emission by the power electronic converter-based drives, voltage at the point of common coupling (PCC) gets distorted and it creates problem for appliances of other industrial and domestic consumers connected at the same PCC. Apart from that the reactive power drawn by non-linear as well as LFP loads also causes the demand charges by the utility to increase and makes voltage regulation poor. This work presents the designing and simulation of a photovoltaic fed Distribution-STATCOM for compensation of harmonics and reactive power of a three phase induction motor based drive. Simulation work has been carried out in MATLAB/Simulink environment. The waveforms and THD data obtained in results verifies the capability of proposed DSTATCOM model for compensating harmonics and reactive power of induction motor drive.

1. Introduction
Three basic operations of electric power system are generation, transmission and distribution of electrical energy. The quality of voltage generated at the utility station in terms of waveform and rated magnitude, is maintained by the generating company (GENCO) itself. With the advancements in technology, use of power electronics has boosted up to considerable extent \[1,2\]. At the same time, due to that excessive use of power electronics converters in different electric drive topologies, harmonics emission and reactive power content in supply current has increased because of their non-linear behavior. A non-linear system is that in which waveforms of input and response are not identical from frequency point of view \[3\]. Due to switching strategies of power electronics converters current does not follow the supply voltage linearly which makes these power electronics converters to draw harmonics as well as reactive power from the supply. The same is done by the electrical drives employing three phase induction motor. In three phase induction motor drives, AC voltage supply is firstly converted to DC by three phase uncontrolled rectifier and the DC voltage obtained is then again converted back to controllable three phase AC voltage by three phase SPWM controlled inverter to operate the induction motor. Control operation of later stage is governed by the
SPWM control circuit. Due to harmonics current drawn by the induction motor drives installed in any industry, voltage of point of common coupling (PCC) is distorted and the operation of other linear loads connected at the same PCC also gets unstable [4]. Due to the voltage distortion in the supply from PCC, operation of others drives gets disturbed since the switching scheme of all the converters is designed according to ideal supply voltage waveform. Further the reactive power drawn also causes poor voltage regulation and thereby the low voltage consumers are supplied at very low voltage. Reactive power increases the demand charges as well paid to the utility grid.

This problem of voltage distortion and poor voltage regulation at PCC can be mitigated by providing the harmonics and reactive power compensation to the induction motor drives system being under operation in a particular industrial plant. The compensation of harmonics and reactive power of load can be done by the application of Distribution STATic COMpensator (DSTATCOM) at PCC [5]. Although power filters those are passive by operation, can also be a substitute of that but they offers compensation to very selected harmonics frequencies and provides limited reactive power support which is not a complete solution. In general each and every custom power device which is employed whether for current quality improvement or voltage quality improvement, always requires either active or reactive power for its operation. In recent years significant importance has been given to application of renewable energy sources (RES) for power quality improvement [6–8]. Apart from that fuel cell, ultra capacitor and flywheel energy storage systems have found their applications in providing energy support to D-STATCOM rather than controlling principle, it draws/supplies a compensation between PV panel and boost converter on requirement basis so that surplus energy can be stored in the battery for night time application purpose. But this work emphasizes more on controlling of DC link voltage and providing energy support to D-STATCOM rather than making optimal utilization of solar energy. Simulation work has been done in MATLAB/Simulink environment. The results achieved verifies effectiveness of DSTATCOM for providing harmonics and reactive power compensation to induction motor drive.

2. Concept of Distribution Static Compensator

The circuit of Distribution Static Compensator (DSTATCOM) mainly consists of a voltage source inverter (VSC) for generating compensation current, an inductor as well as DC capacitor for reactive power storage. At the same time capacitor also acts as energy storage bank for DSTATCOM. In accordance with the switching algorithm, inverter gets the direction for transmission of energy form DC capacitor to system and back through the inductor [12]. Figure 1 demonstrates the basic scheme of compensation by a DSTATCOM. According to the controlling principle, it draws/supplies a compensation current \( I_c \) from and to the system and thus discontinues the supply of current components of harmonics as well as reactive power form the supply side. In this manner sets the supply current \( I_s \) to purely sinusoidal one and also in same phase of the supply voltage. Equation no. 1 correlates those three currents.

\[ I_s = I_l - I_c \]  

The waveforms of three current components are shown in Figure 2. First waveform is for the load current \( I_l \)}
which is taken by the load and second waveform is the desired supply current $I_s$. Third waveform shows the compensating current $I_c$ injected by the DSTATCOM which comprises the total harmonics and reactive components of load current.

3. Proposed Photovoltaic Based Dstatcom

There are two core parts of every DSTATCOM system. First is the reference current detection and second one is the injection of the compensator current according to that [13]. For the purpose of compensation of harmonics and reactive power current drawn by the load, the first requirement is the precise detection of reference current and it preforms very crucial role in the load compensation by DSTATCOM since wrong reference current detection can cause the DSTATCOM to become a source of disturbance itself. After detection of reference current voltage source inverter (VSI) generates similar current components after tracking and that current is controlled by hysteresis current controller. The current generated by the VSC is injected in to the load at PCC by the shunt connected transformer. For precise tracking of the reference current by the current controller, voltage of DC link is very essential to be maintained at constant value. The DSTATCOM model proposed in this work makes utilization of solar energy for load compensation and controlling the DC link voltage. Figure 3 shows complete configuration of the proposed model of DSTATCOM. The key parts of the proposed model are explained as follows.

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**Figure 1.** Basic compensation principle of DSTATCOM.

**Figure 2.** Waveforms of load, supply and injected compensation current.
3.1. Reference Current Detection

Targeting at the detection of reference current many theories have been recommended in literature. One among them is the instantaneous reactive power theory (IRP) and also famous by the name of PQ-theory [14,15]. Figure 4 shows the flow chart for detection of reference current by PQ-theory. In this theory first three phases Clarke transformation of supply side voltage and current is done [16].

Current and voltage of the system are converted into α–β the system using the following Equation (2).

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix} \begin{bmatrix}
i_a^* \\
i_b^* \\
i_c^*
\end{bmatrix}
\]

(2)

After that transformation instantaneous active and reactive power is calculated as per Equations (3) and (4).
\[ p = v_a i_o + v_\alpha i_\alpha + v_\beta i_\beta \]  \hspace{1cm} (3)

\[ q = v_\alpha i_\beta - v_\beta i_\alpha \]  \hspace{1cm} (4)

After calculating the instantaneous active and reactive power oscillating components of active as well as reactive power are filtered using the low pass filter.

\[ p = \bar{p} + \tilde{p}, q = \bar{q} + \tilde{q} \]  \hspace{1cm} (5)

The filtered components further gives the components of current those are required to be supplied by the DSTATCOM after tracking through hysteresis loop controller based voltage source converter. For keeping the voltage of dc link of VSC at constant value, switching loss component is added to active power that is delivered from the source side. Maintaining the constant voltage at the dc link is must for precise tracking of reference current by hysteresis loop controller [17].

### 3.2. Hysteresis Current Controller Designing

In the system of power distribution, harmonics and reactive power are present mainly due to the nonlinear loads. By the application of DSTATCOM, one can reduce the requirement of harmonics as well as reactive power of the load from source point of view. At the same time VSC alone is not sufficient to lessen the harmonics requirement of the load. Therefore certain controller is necessary to lessen the harmonics and reactive power drawn up to more extent. A number of controllers are reported in literature to lessen the THD.

In present work hysteresis current controller has been deployed for compensating the harmonics and reactive power requirement of the load. First the load current is provided to RMS block in addition to PLL-block [18]. This gives the load current’s fundamental frequency by the PLL-block. Than multiplication of this current is done with RMS of the load current and the output current gets deducted from the load current. After this, we get the harmonics and reactive power component of current. That harmonic and reactive power component of current will be supplied to the hysteresis controller in form of a reference current (i\textsuperscript{ref}). The output current of filter is also given to the hysteresis controller in form of current measured (i\textsuperscript{meas}). In the hysteresis controller the difference b/w i\textsuperscript{meas} and i\textsuperscript{ref} is taken and given to hysteresis band, and form there we get the switching pulses for the inverter to provide the inverter power losses and to keep the voltage of DC-link under the desired range.

Figure 5 shows schematic diagram of DSTATCOM with hysteresis current controller. Figure 6 displays the simulation illustration consisting of that hysteresis current control system. The scheme of controlling governs the pattern of switching for DSTATCOM in the way to keep the actual source current of the filter within a fixed hysteresis band (HB) as indicated in Figure 6.

### 3.3. Voltage Control of Photovoltaic Fed DC Link

For uninterrupted compensation of load by DSTATCOM, it is essential to sustain DC link voltage at a constant value [19]. In present work, voltage of DC link is maintained constant by boosting the voltage of

![Figure 5](image-url) Schematic diagram of DSTATCOM with hysteresis current controller.
PV panel regardless of any change in irradiation and temperature. For controlling the boost converter a PI controller based closed loop control system has been used. In the control strategy, converter output is compared with the reference value of DC link voltage and according to that difference the output of PI-controller is compared with high frequency carrier signal and pulses are fed to the switching circuit of the boost dc to dc converter. Figure 7 shows the control scheme of boost converter. In this manner photovoltaic fed dc link voltage get controlled in an appropriate way as well the compensator utilizes solar energy for its operation.

4. Matlab Results of Simulation and Discussion

For validating the usefulness of proposed photovoltaic based model of DSTATCOM in compensating the harmonics and reactive power requirement of three phase induction motor drive, all the simulation work of this paper has been done in matlab/simulink. Table 1 displays the selected simulation parameters. Figure 8 displays the matlab/simulink based model of proposed DSTATCOM applied for compensating the harmonics and reactive power of three phase induction motor drive. Figure 9 shows matlab/simulink-based model of PV array cascaded with boost inverter for controlling the DC link voltage. Figure 10 (a–d) shows the waveform of supply voltage, supply current, compensation current and load current respectively. Figure 11 shows the waveform of supply voltage and current per phase on the common axis after the compensation by the proposed model of DSTATCOM. Figure 12 shows the waveforms of three phase instantaneous active and reactive power flowing from the source side after the compensation by the proposed model of DSTATCOM. Figure 13 shows the THD analysis of supply current after compensation by the proposed model of photovoltaic

Table 1. Simulation parameter of system.

| Parameter                        | Values                                      |
|----------------------------------|---------------------------------------------|
| Voltage of Supply                | 4.1 kV (Line), 60 Hz.                       |
| Parameters of Feeder             | L_s = 0.4 mH, R_s = 0.6457 Ω                |
| Load (Non-linear)                | 3-phase induction motor drive               |
| DC-Capacitor                     | 540 μF                                       |
| Inductor for Interfacing         | L_f = 6.6 mH, R_f = 0.7 Ω                  |
| Reference Voltage at DC-link     | V_{dc} = 430                                 |
| Parameters of PI-Controller      | K_p = 3.7, K_i = 0.9                         |
| No. of Solar Panels in parallel  | 4                                           |
| Rated Voltage of Each Panel      | 12 V each                                   |
| Maximum Power                    | 65 W each                                   |
| Maximum Voltage                  | 24.5 V                                      |
Figure 8. MATLAB/Simulink based model of photovoltaic based DSTATCOM.

Figure 9. Matlab/simulink based model of PV array cascaded with boost inverter.
Figure 10. (a–d) Waveforms of supply voltage, supply current, compensation current and load current.
based DSTATCOM and Figure 14 shows the waveform of controlled DC link voltage.

For controlling the DC link voltage and providing solar energy support to the compensator total four panels are connected in parallel and their output voltage is boosted by the boost converter. Duty cycle of boost converter is controlled for controlling the voltage of DC link as shown in simulation diagram.

Figure 10(b) shows that after compensation by the proposed photovoltaic based DSTATCOM source current is very close to sinusoidal shape and as per Figure 13 THD of the source current has been found 1.29 % that is under the IEEE standard 519. Figures 11 and 12 shows that after compensation by the DSTATCOM supply voltage and current are in same phase and instantaneous reactive power drawn from the source side is very less and only average component of instantaneous active power is drawn from the source side. Figure 14 shows the effectiveness of control strategy of proposed DSTATCOM model in regulating the DC link voltage as well.

5. Conclusion

The designing and simulation work of a photovoltaic fed Distribution-STATCOM for harmonics and reactive power compensation of three phase induction motor drive has been presented. The waveforms obtained verify the usefulness of proposed model of DSTATCOM in harmonics and reactive power compensation of three phase induction motor drive. Total harmonics distortion (THD) of supply current after compensation by DSTATCOM has been found 1.29 % which is under IEEE standard-519. Thus the proposed DSTATCOM system can be an effective solution for voltage quality improvement at power distribution point of an industrial area. Future scope
of the present work is the implementation of fuzzy logic based controller for PV fed boost converter and its comparison with the presented work from DC link voltage control point of view. Other renewable energy source can also be tested for providing energy support to the compensator.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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