Improved Performance of MCUPQC with PV System for Power Quality Improvement in Distributed Generation Network

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Abstract—Industrialization demands for an increased electrical power generation. As the conventional power generating stations cannot meet the total demand, the distribution generating stations have received more importance by electrical power utilities. In this context, distributed generation gained lot of attention as an alternative solution for the generation near the load center. The power generated from these sources like wind, solar, tidal etc. are having power quality issues like harmonics, sag/swell. In this paper, the PV System connected through MCUPQC is termed as MCUPQC-PV, to assure better quality and reliability of power. This system helps in to compensate reactive power, harmonic distortions, reduction in installation cost of PV system and rating of VSC. MCUPQC-PV also transfers active power to the load and source in interconnected and islanding mode to compensate the voltage interruption in multi feeders. The proposed distribution system fed by PV with MCUPQC for power quality improvement and reliability is analyzed and results are present using MATLAB/Simulink.

Keywords — Multi Converter Unified Power Quality Conditioner (MCUPQC), Voltage Source Converter(VSC), Power Quality(PQ), Photovoltaic array (PV), Super Capacitor(SC).

I. INTRODUCTION

The growing demand due to industrial revolution is posing a challenge to the electrical power utilities. Hence knowing the fact that this demand cannot be met only by the bulk power conventional generating systems, the renewable energy systems gained momentum. In this direction, the electrical power utilities started depending on the distributed power generating units. Moreover the increasing utilization of power by non-linear loads, unbalanced loads, modern semi conductor devices like thyristors, etc., led to power quality issues like sag, swell and harmonic distortion etc. Even for variable switching times of loads will also causes voltage disturbances.

Power Quality problem are majorly classified as harmonics generation, reactive power usage in line increasing, poor power factor, distortions in voltage waveform. [3], [4].

To get rid of these problems, compensation techniques used which provide the compensation in series connection as well as in parallel connection which are termed as series, shunt compensation. The compensation taken with parallel connection that minimizes harmonics, nullifies the unbalanced current components flowing in neutral point. The compensators connected in series connection increases the supply voltage characteristics by improving the waveform. [5].

The inherent characteristics of UPQC i.e. both series, shunt compensation techniques provides solution to the power quality problems, duly ensuring efficiency and economy [6], [7]. For supplying DC link provided PV system is used. By using shunt compensator PV’s power is fed to loads as shunt active power filter. Mostly wind, solar distributed generation systems as availability of input source [8]-[11]. Fig. 1 shows the block diagram of the MCUPQC-PV in distribution generation network.

The technical, environmental and economical advantages of the PV system is that it allows installation of the small and medium scale power generations at low/medium voltage distribution systems [12]. In recent years, photovoltaic based power generation gained momentum as a solution to the distributed generation system due to the reduced investment [13]. Small Capacities of PV Systems are globally accepted as DG systems at sub transmission voltage levels.

Fig. 1 Block diagram of MCUPQC with PV System
In this paper, the new connection of a MCUPQC integrated with PV system is presented[14]-[16]. This system consists of two series and one shunt voltage source converters are share the power from common dc link capacitor. Therefore the voltage swell/sag, voltage interruptions, harmonics and reactive power are compensated under both modes of operation [17]-[19].

II. PROPOSED MCUPQC WITH PV SYSTEM

A. Circuit Structure

The MCUPQC-PV is connected in between source bus and load bus of two feeders. Fig.2. shows the block diagram of proposed test system. To compensation the harmonic content injected in to the source by the load is done using shunt compensator VSC2 at load side. For having good voltage profile at loads the sag/swell conditions in source voltage are mitigated by series compensators VSC1 and VSC3. \( u_{df} \) is the voltage compensated by series controller and \( I_{pf} \) is the current injected by shunt controller to meet reactive power demand of the load.

By using VSC type converters system efficiency can be increased with high stability and used to control active and reactive power individually. The normal structure of PV system is directly connected to the grid as shown in Fig.4.

B. MCUPQC-PV with Super Capacitor Structure

As show in Fig. 3 the proposed system consist of a two series VSCs and one shunt VSC connected to common dc link capacitor. BUS1 having series connection with VSC1 in series and other VSC2 in shunt with load at the load bus and BUS2 having series connection with VSC3.

The DC link is connected for sources developed from PV system which feed the MCUPQC. For compensating power quality and reliability issues PV fed power is used.

Fig. 2 MCUPQC with PV Connected System

Fig. 3 The proposed Configuration of MCUPQC-PV System

Each of the three voltage source converters are realized by a three-phase converter with high-pass output filter and a commutation reactor as shown in Fig. 5. The high-pass output filter(\( R_f, C_f \)) and smoothing reactor(\( L_s \)) are connected to reduce the flow of switching harmonics in the power supply.

Fig. 4 The normal structure of PV system connected to grid
The main functions of the MCUPQC-PV with super capacitor are:
1) To transfer active power to the load and grid under islanding mode to protect sensitive critical load under source voltage interruption.
2) To regulate the voltage across the load from swell/sag disturbances in the system to protect the sensitive nonlinear load and critical load.
3) To compensate the reactive power content and harmonic content of nonlinear load current.

III. CONTROLLER DESIGNING
The controlling structure of proposed system is composed of three following parts:
A. Shunt VSC 2
B. Series VSC1 & VSC3
C. DC/DC converter

Controlling strategy is designed and applied for two interconnected and islanding modes. In interconnected mode, source and PV provide the load power together while in islanding mode; PV transfers the power to the load lonely. By removing voltage interruption, system returns to interconnected mode.

A. Shunt VSC 2
Functions of the shunt-VSC 2 are:
1. To compensate for the reactive component and the harmonic component of load current.
2. To compensate for interruptions and is inject the active power generated by PV system to the load.

I. Shunt VSC2 in Interconnected Mode:
Fig. 6 shows the control block diagram for the shunt voltage source converter. The measured load current \(i_{abc}\) is transformed into the synchronous dqo reference frame by using,
\[
I_{L,dqo} = T_{dqo}^{abc} i_{abc}
\]
Where the transformation matrix \(T_{dqo}^{abc}\) is
\[
T_{dqo}^{abc} = \frac{2}{\sqrt{3}} \begin{bmatrix}
\cos(\omega t) & \cos(\omega t - 120^\circ) & \cos(\omega t + 120^\circ) \\
-\sin(\omega t) & -\sin(\omega t - 120^\circ) & -\sin(\omega t + 120^\circ)
\end{bmatrix}
\]

By this transform, the fundamental positive-sequence component, which is transformed into dc quantities in the \(d\) and \(q\) axes, can be easily extracted by low-pass filters (LPFs). Also, all harmonic components are transformed into ac quantities with a fundamental frequency shift
\[
i_{L,d} = \tilde{i}_{L,d} + i_{L,d}
\]
\[
i_{L,q} = \tilde{i}_{L,q} + i_{L,q}
\]
Where \(i_{L,d}\) and \(i_{L,q}\) are d-q components of load current, \(\tilde{i}_{L,d}\) and \(\tilde{i}_{L,q}\) are dc components, and \(i_{L,d}\) and \(i_{L,q}\) are the ac components of \(i_{L,d}\) and \(i_{L,q}\). If \(i_s\) is the feeder current and \(i_{pf}\) is the shunt voltage source converter current and knowing \(i_s = i_s - i_{pf}\), then d-q components of the shunt voltage source converter reference current are defined as follows:
Consequently, the \( d-q \) components of the feeder current are

\[
i_{d}\text{, }q = i_{l}\text{, }q
\]

This means that there are no harmonic and reactive components in the feeder current. Switching losses cause the dc-link capacitor voltage to decrease. Other disturbances, such as the sudden variation of load, can also affect the dc link. In order to regulate the dc-link capacitor voltage, a proportional–integral (PI) controller is used as shown in Fig. 6. The input of the PI controller is the error between the actual capacitor voltage \( (u_{dc}) \) and its reference value \( (u_{dc}^{ref}) \). The output of the PI controller (i.e., \( \Delta i_{dc} \)) is added to the component of the shunt voltage source converter reference current to form a new reference current as follows:

\[
i_{pf, d}^{ref} = i_{l,d} + \Delta i_{dc}
\]

\[
i_{pf, q}^{ref} = i_{l,q}
\]

As shown in Fig. 6, the reference current in (9) is then transformed back into the \( abc \) reference frame. By using PWM hysteresis current control, the output compensating currents in each phase are obtained [19].

\[
i_{pf, abc}^{ref} = T_{abc}^{dqa}i_{pf, d}^{ref} = T_{abc}^{dqa}i_{pf, q}^{ref}
\]

2. Shunt VSC2 in islanding mode:

If voltage interruption occurs, the shunt inverter's operation will switch from interconnected mode to islanding mode. PV system provides required active power to stabilize load voltage. In this case, shunt inverter controls output voltage and current in order to inject to load using PI controller. Fig. 6 shows the block diagram of shunt inverter control based on the above relations to control the shunt inverter during voltage interruption and islanding mode.

B. Series VSC1 & VSC3

Functions of the series voltage source converter are:

1) To mitigate voltage sag and swell.
2) To compensate for voltage distortions, such as Harmonics.

The control block diagram of series voltage source converter is shown in Fig. 7. The bus voltage \( (u_{t,dq0}) \) is detected and then transformed into the synchronous \( dq0 \) reference frame using

\[
u_{t,dq0} = T_{dq0}^{abc}u_{t,abc} = u_{t1p} + u_{t1n} + u_{t10} + u_{th}
\]

Where

\[
u_{t1p} = \begin{bmatrix} u_{t1p,d} & u_{t1p,q} & 0 \end{bmatrix}^T
\]

\[
u_{t1n} = \begin{bmatrix} u_{t1n,d} & u_{t1n,q} & 0 \end{bmatrix}^T
\]

\[
u_{t10} = \begin{bmatrix} 0 & 0 & u_{00} \end{bmatrix}^T
\]

\[
u_{th} = \begin{bmatrix} u_{th,d} & u_{th,q} & u_{th,0} \end{bmatrix}^T
\]

\[
u_{t1p}, \nu_{t1n}, \text{ and } \nu_{t10} \text{ are fundamental frequency positive, negative, and zero sequence components, respectively, and } u_{th} \text{ is the harmonic component of the bus voltage. According to control objectives of the UPQC, the load voltage should be kept sinusoidal with constant amplitude even if the bus voltage is disturbed. Therefore, the expected load voltage in the synchronous dq0 reference frame (}\nu_{t,dq0}^{ref}\text{) only has one value.}

\[
u_{t,dq0}^{exp} = T_{dq0}^{abc}u_{t,abc}^{exp} = \begin{bmatrix} U_m \\ 0 \\ 0 \end{bmatrix}
\]

Where the load voltage in the \( abc \) reference frame (\( u_{t,abc}^{exp} \)) is

\[
u_{t,abc}^{exp} = \begin{bmatrix} U_m \cos(\omega t) \\ U_m \cos(\omega t - 120) \\ U_m \cos(\omega t + 120) \end{bmatrix}
\]
The compensating reference voltage in the synchronous dqo reference frame \( u_{c,dqo}^{ref} \) is defined as
\[
 u_{c,dqo}^{ref} = u_{c,dqo} - u_{dqo}^{exp}
\]  
(15)

This means \( u_{1p,d} \) in (12) should be maintained at \( U_m \) while all other unwanted components must be eliminated. The compensating reference voltage is transformed back into the abc reference frame. By using an improved SPWM voltage control technique, the output compensation voltage of the series VSC can be obtained.

C. DC/DC Converter Controlling to Obtain the Maximum Power of PV Array:

PV systems are nonlinear power sources whose output power is greatly under effect of two radiation and environment temperature elements. One of the disadvantages of the system is their low efficiency, because solar cells rarely operate at their maximum power point. So in order to increase the efficiency, as much power as possible should be extracted from the array. Temperature variation effects on cell voltage and radiation variation effects on cell current. Fig. 8 shows the equivalent circuit of PV array used in simulation.

In connection of the PV array to grid, a DC/DC converter is applied and is used to adapt the variable voltage of PV with the voltage of grid and extract the maximum power from the array. In respect to Fig. 9 MPPT is obtained by controlling the duty cycle of DC/DC converter switch. In this paper, algorithm of perturbation and observation (P&O) method is one of the most common method used to achieve the maximum power point. In P&O method, a short perturbation is created in array's output voltage and then output voltage is measured. If this perturbation causes an increase in output power, then the next perturbation will be applied in this direction, and if it causes reduction, then voltage perturbation will be applied in reverse direction and this process continues till achieving the maximum power point of the array. The advantage of this method is simple operation. The duty cycle of converter switch is determined by measuring voltage and array's current values in specific periods of time.

![Fig. 9 Schematic diagram of MPPT of PV array](image)

![Fig. 8 Equivalent circuit of PV array](image)

![Fig. 10 Bus voltage, series compensating voltage and load voltage](image)

IV. SIMULATION RESULTS

The proposed MCUPQC-PV and its control schemes have been tested through extensive case study simulations using MATLAB. In this section, simulation results are presented, and the performance of the proposed MCUPQC-PV system is shown.

A. Distortion and Sag/Swell on the Bus Voltage

Let us consider that the power system as shown in Fig. 2, consists of three-phase three-wire 380V (rms, L-L), 50Hz utilities. The BUS1 voltage contains the seventh-order harmonic with a value of 22%, voltage contains 25% swell between 0.1s < t < 0.2s and 25% sag between 0.25s < t < 0.35s.

The MCUPQC-PV is switched on at 0.02 s. The BUS1 voltage, the corresponding compensation voltage injected by VSC1, and finally load voltage are shown in Fig. 10. As shown in these figures, distorted voltage of BUS is satisfactorily compensated across the load with very good dynamic response. The dc voltage regulation loop has functioned properly under all disturbances, such as sag/swell.
B. Upstream Fault on Feeder2

When a fault occurs in Feeder2 (in any form of L-G, L-L-G, and L-L-L-G faults), the voltage across the non linear sensitive/critical load is involved in sag/swell or interruption. This voltage imperfection can be compensated by PV source through VSC3.

In this case, the power required by load is supplied through PV system and VSC3. This implies that the power semiconductor switches of VSC1 and VSC2 must be rated such that total power transfer is possible. This may increase the cost of the device, but the benefit that may be obtained can offset the expense. In the proposed configuration, the sensitive critical load on Feeder2 is fully protected against distortion, sag/swell, and interruption. Furthermore, the regulated voltage across the sensitive load on feeder can supply several customers who are also protected against distortion, sag/swell, and momentary interruption. Therefore, the cost of the MCUPQC-PV must be balanced against the cost of interruption, based on reliability indices, such as the customer average interruption duration index (CAIDI) and customer average interruption frequency index (CAIFI). It is expected that the MCUPQC-PV cost can be recovered in a few years by charging higher tariffs for the protected lines.

The performance of the MCUPQC-PV under a fault condition on Feeder2 is tested by applying a three-phase fault to ground on Feeder2 between 0.4s<t<0.5s. Simulation results are shown in Fig. 11.

Fig. 11 Simulation result for upstream fault on feeder: Bus voltage, compensating voltage and load voltage

C. Load Change

To evaluate the system behavior during a load change, the nonlinear load is doubled by reducing its resistance to half at t= 0.6s. It can be seen that as load changes suddenly and the load voltage is remain undisturbed, the dc bus voltage is regulated, and the nonlinear load current is compensated.

The nonlinear load current, its corresponding compensation current injected by VSC2, load voltage, and finally, the dc-link capacitor voltage are shown in Fig. 12. The distorted nonlinear load current is compensated very well, and the total harmonic distortion (THD) of the feeder current is reduced from 26.5% to less than 5%.

Fig. 12 Simulation results for load change: nonlinear load current, feeder current, load voltage

V. CONCLUSION

The new configuration is named as MCUPQC integrated with PV System (MCUPQC-PV). This configuration is capable of protecting sensitive critical loads against distortions, sags/swell and interruption in both islanding and interconnected modes. MCUPQC-PV performance is examined under different disturbance conditions and it offers the following advantages:

1) It balances or regulates load voltage against sags/swell and disturbances in the system to protect non linear sensitive loads.
2) It compensates harmonic and reactive component currents of non linear load.
3) It compensates voltage interruption and it ensures the active power transfer to the load and grid in island mode to protect non linear critical load.
4) The cost can be reduced up to margin of one fifth for a combined system depending upon the rating.

The capacity enhancement can be achieved using multi level configuration. The flexibility of MCUPQC-PV, to increase its capacity to meet increase load demand of medium voltage distribution system in future and meet the economic growth of country.
TABLE I
MCUPQC-PV SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Quantities</td>
<td></td>
</tr>
<tr>
<td>System fundamental frequency (f)</td>
<td>50Hz</td>
</tr>
<tr>
<td>Voltage source (U_s)</td>
<td>380V (L-L rms) phase angle of 0°</td>
</tr>
<tr>
<td>Feeder Impedance (Rs+j2πfLs)</td>
<td>1+j0.314Ω</td>
</tr>
<tr>
<td>Load (L) Non-Linear/Sensitive Load</td>
<td>A three-phase diode rectifier that supplies a load of R=10Ω, L=30μH</td>
</tr>
<tr>
<td>Series VSC-1 single phase Transformers</td>
<td>5KV, linear type, 10% Leakage reactance</td>
</tr>
<tr>
<td>Shunt VSC-2 single phase Transformers</td>
<td>10KV, linear type, 10% Leakage reactance</td>
</tr>
<tr>
<td>Filter Capacitor(C_f)</td>
<td>100μF</td>
</tr>
<tr>
<td>Filter Resistor (R_f)</td>
<td>0.1 Ω</td>
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<tr>
<td>Commutation Reactor(L_c)</td>
<td>50mH</td>
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<tr>
<td>DC Capacitor(C_d)</td>
<td>2000 μF</td>
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<tr>
<td>PV Array Rating</td>
<td>40kW</td>
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<tr>
<td>V_dcref</td>
<td>600V</td>
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</table>

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REFERENCES


