Economic Assessment of Unified Power Quality Controller Operation in Joint and Separated Modes with DG Units

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Abstract: This study evaluates the joint operation of the Unified Power Quality Conditioner (UPQC) and distributed generation system with there separated operation and compares these modes from economic point of view. The investigated joint system consists of a series inverter, a shunt inverter, and an DG unit connected in the dc link through a rectifier. The separated system consists of a separate UPQC and DG unit which is connected to grid through back to back inverters. The investment cost of joint system is compared with investment cost of separate use of UPQC and DG unit and the economic saving due to use of coupled system is estimated. The DG unit is assumed a Wind Energy Conversion System (WECS) in this study. The analysis shows that joint operation of UPQC with WECS is significantly economical.

Key words: Back to back inverter, investment cost, va rating, wind energy

INTRODUCTION

Two back-to-back connected dc/ac fully controlled converters is one of the most interesting structures of energy conditioners. In this case, depending on the control scheme, the converters may have different compensation functions. For example, they can function as active series and shunt filters to compensate simultaneously load current harmonics and supply voltage fluctuations. In this case, the equipment is called Unified Power Quality Conditioner (UPQC) (Akagi et al., 2007; Aredes and Watanabe, 1995; Fujita and Akagi, 1998; Han et al., 2006).

An active shunt filter is a suitable device for current-based compensation (Fujita and Akagi, 1998). It can compensate current harmonics and reactive power. The active series filter is normally used for voltage harmonics and voltage sags and swells compensation (Fujita and Akagi, 1998). The UPQC, which has two inverters that share one dc link capacitor, can compensate the voltage sag and swell, the harmonic current and voltage, and control the power flow and voltage stability. Nevertheless, UPQC cannot compensate the voltage interruption due to lack of energy source in its dc link (Han et al., 2006).

Nowadays, generation of electricity from renewable sources has improved very much. Utilizing of wind energy as a renewable source to generate electricity has developed extremely rapidly and many commercial wind generating units are now available on the market. The cost of generating electricity from wind has fallen almost 90% since the 1980s (Karrari et al., 2005). Wind is a variable and random source of energy. All types of machines, i.e., dc, synchronous, induction, depending on the size of the system have been used to convert this form of energy to electrical energy. Induction generators are more common and more economical by improvement of power electronics devices and drive methods (Datta and Rangenathan, 2002).

Various forms of systems can be used to have some level of control on the wind generation unit. In the variable speed constant frequency systems, power electronic devices are used to allow the rotor speed to be changed while the grid frequency is constant. In one scheme, as assumed in this paper, a Variable Speed Cage Machine (VSCM) system is used with back to back inverters connecting the cage induction generator stator to the grid (Bana sharifian et al., 2008). The advantage of the variable speed constant frequency system is that the rotor speed can be controlled. This makes it possible to capture maximum energy from the wind turbine (Karrari et al., 2005; Datta and Rangenathan, 2003; Kim and Kim, 2007). As the rectifier allows the change of the rotor flux, the operator can also maximize the efficiency of the induction generator.

Some research papers are now available on UPQC and distributed generation. In (Han et al., 2006) a new coupled UPQC and synchronous generator is proposed, in which the synchronous generator is connected to UPQC DC bus through an uncontrolled rectifier. In (Cavalcanti et al., 2005) a photovoltaic generation system with unified power quality conditioner function has been proposed, in which the PV system is connected to UPQC DC bus and UPQC transfers PV's generated active power to grid. In this study the decoupled operation of UPQC and wind energy generation systems with coupled operation of them as shown in Fig. 1 has been economically analyzed and
MATERIALS AND METHODS

The goal of this paper is economical comparison of decoupled and coupled operation of UPQC and WECS and estimate the economic saving due to use of coupled system. To reach this aim, at fist the phasor diagram of UPQC has been evaluated. Then VA rating calculation of shunt and series inverter has been investigated. After that, Effect of connecting DG to UPQC on UPQC converters VA has been evaluated and finally at the results and discussion session, economic analysis of linking DG with UPQC has been analyzed.

Phasor diagram of UPQC: Figure 2 shows phasor diagram of shunt inverter of UPQC for fundamental power frequency when the supply voltage equals the desired load voltage (Basu, 2007).

When the supply voltage has no deficiency; \( V_{s1} = V_{l1} = V_{s2} = V_{l2} \) (a constant), and the series injected voltage \( V_{m} \) requirement is zero. This state is represented by adding suffix “1” to all the voltage and current quantities of interest. The load current is \( I_{l1} = I_{l} \) and the shunt inverter compensates the reactive component \( I_{c1} \) of the load, resulting in unity input power factor. Thus, the current drawn by the shunt inverter is \(-I_{c1}\) which is opposite to the load reactive current \( I_{c1} \). As a result, the load always draws the in-phase component \( I_{s1} \) from the supply. For non-linear loads, the shunt inverter not only supplies the reactive current, but also the harmonic currents required for the load. Thus, after the compensation action of the shunt inverter, only the fundamental active component of the current is required to be supplied from the utility.

As soon as the load voltage \( V_{l} \) sags, the UPQC is required to take action to compensate for the sag, so that \( V_{l} \) is restored to its desired magnitude. This condition is represented by adding suffix “2” to the parameters. Consequently the load current changes to \( I_{l2} \). The shunt inverter injects \( I_{c2} \) in such a way that the active power requirement of the load is only drawn from the utility. Therefore, from the utility side the load power factor is always unity. It can be observed from the phasor diagram that the utility current is \( I_{s2} \), and is in phase with \( V_{s2} \). If the active power demand is constant, \n
\[
V_{s2} I_{s2} = V_{s1} I_{s1} = V_{l1} I_{l1} = V_{l2} I_{l2}
\]

which can be written as:

\[
V_{s2} I_{s2} = V_{s1} I_{s1} = V_{l1} I_{l1} = V_{l2} I_{l2}
\]
VA rating calculation of shunt and series inverter:
Volt ampere (VA) rating of series and shunt inverters of UPQC determines the size of the UPQC. The power loss is also related to the VA loading of the UPQC. Here, the loading calculation of shunt and series inverters of UPQC with presence of DG at its dc link has been carried out on the basis of linear load for fundamental frequency. The load voltage is to be kept constant at $V_o$ p.u. irrespective of the supply voltage variation:

$$V_s = V_{12} = V_{s1} = V_o \text{ P.U} = v_l$$

(3)

The load current is assumed to be constant at the rated value:

$$I_L = I_{k1} = I_{k2} = I_o \text{ P.U}$$

(4)

Assuming the UPQC to be lossless, the active power demand in the load remains constant and is drawn from the source:

$$V_s I_s = V_L I_L \cos \phi$$

(5)

In case of a sag when $V_{s2} \lt V_{s1}$, where $x$ denotes the p.u. sag,

$$V_{s2} = (1-x)V_{s1} = V_o(1-x) \text{ P.u}$$

(6)

to maintain constant active power under the voltage sag condition as explained in (1)

$$I_{s2} = \frac{V_{s1} I_s \cos \phi}{V_{s2}(1-x)} = \frac{I_o \cos \phi}{1-x} \text{ P.u}$$

(7)

therefore series inverter VA rating equals to:

$$S_{s\text{ser.}} = V_o I_{s2} \frac{V_{s2} \cos \phi}{1-x} \text{ p.u}$$

(8)

 Injected current through shunt inverter is:

$$I_{c2} = \sqrt{I_{L1}^2 + I_{s2}^2} = 2I_{k1}I_{k2} \cos \phi$$

(9)

therefore shunt inverter VA rating equals to:

$$S_{s\text{sh.}} = V_o I_{c2} \frac{1}{1-x} \sqrt{(1-x)^2 + \cos^2 \phi(1-2(1-x))} + I_o \frac{(1-x)^2 + \cos \phi(1-2(1-x))}{(1-x)^2} Z_{sh}. \text{ p.u}$$

(10)

As observed from Fig. 4, it is seen that loading on the series inverter increases as % sag increases. The series inverter maximum loading will be 1 p.u. (based on maximum loading at 50% sag at unity power factor of load's power factor) to successfully cater the mentioned region of voltage sag under the specified power factor variation. From Fig. 5 it is observed that the maximum loading condition occurs at similar condition mentioned above. Maximum shunt inverter rating is 1 p.u.
Effect of connecting DG to UPQC on UPQC converters VA: By connecting DG to the DC link of UPQC, the active power required by series inverter can be supplied from DG. Hence, the freed capacity created on the shunt inverter can be used for active power flow (transmission) to grid. These capacities of inverters are detailed as follows.

From Fig. 8 one can deduce that the current in shunt inverter which compensates voltage drop in dc link due to operation of series inverter, is parallel with ISI whose vector sum with I_C1 will yield I_C2. That would be active current in the direction of ISI and its rms value is I_SE - C2 which is equal to vector difference of I_C1 and I_C2:

$$I_{SE-C2} = \sqrt{I_{C2}^2 - I_{C1}^2}$$  \hspace{1cm} (11)

From fig. 8 it can be found that:

$$I_{C1} = I_o \sin \phi$$  \hspace{1cm} (12)

By substituting I_C1 and I_C2 from (34) and (31) respectively, I_SE - C2 is equals to:

$$I_{SE-C2}^2 = I_o^2 (1-x)^2 + \cos^2 \phi [1-(1-x)]^2 - I_o^2 \sin^2 \phi$$  \hspace{1cm} (13)

Simplifying (13) results in:

$$I_{SE-C2} = I_o \frac{\cos \phi}{1-x} \ p.u$$  \hspace{1cm} (14)

Assuming, I_o = 1 p.u the value of I_SE - C2 will be given for different values of load power factor. Table 1 demonstrates the per unit active current in the shunt inverter for series compensation for different power factors and voltage sag values. By installing DG on DC link of UPQC and supplying active power required for series compensation by DG, the active power of DG can flow to grid through shunt inverter. Assuming shunt inverter design of 1 p.u capacity for complete current compensation and voltage sag compensation up to 0.5 p.u, by connecting DG to the UPQC dc link, 1 p.u shunt Table 2 shows the possible inverter will be able to flow 1 p.u current of DG to grid. capacity of shunt inverter for carrying Dg active current for different power factor values. Therefore the proposed configuration is capable of DG active power transmission of 1 p.u to the grid without any change in the capacity of series and shunt inverters.

<table>
<thead>
<tr>
<th>( \cos \phi )</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
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<tr>
<td>( \cos \phi )</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>( \cos \phi )</td>
<td>0.655</td>
<td>0.126</td>
<td>0.213</td>
<td>0.357</td>
<td>0.50</td>
<td></td>
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<tr>
<td>( \cos \phi )</td>
<td>0.666</td>
<td>0.150</td>
<td>0.255</td>
<td>0.400</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>( \cos \phi )</td>
<td>0.777</td>
<td>0.175</td>
<td>0.300</td>
<td>0.500</td>
<td>0.80</td>
<td></td>
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<tr>
<td>( \cos \phi )</td>
<td>0.888</td>
<td>0.200</td>
<td>0.342</td>
<td>0.533</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>( \cos \phi )</td>
<td>0.999</td>
<td>0.225</td>
<td>0.385</td>
<td>0.600</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>( \cos \phi )</td>
<td>1.150</td>
<td>0.250</td>
<td>0.428</td>
<td>0.667</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

In this section, the economic analysis of separate linking of UPQC and DG to distribution network by coupled scheme (as discussed in this paper) is carried out and compared. In the coupled operation of UPQC and DG, an inverter is used less compared to the separate operation of them. On the other hand, there is no need for DG converter and its duty is done by shunt inverter. The shunt inverter transmits the active power of DG to grid besides compensating the reactive power and harmonics of load current without increase of shunt inverter rating.

The investment cost of inverter \( I_{elec} \) can be expressed as (Kaldellis and Kavadias, 2007):

$$I_{elec} = 2N_p^{1-t} \lambda = 483($ / $w)$$  \hspace{1cm} (15)

$$t = 0.08.$$

which \( N_p \) is the rated power of inverter. Since UPQC has two inverters, the investment cost of UPQC is same as two inverters. The investment cost of wind turbine by rated power of \( N_{WT} \), can be demonstrated by (Kaldellis and Kavadias, 2007):

$$I_{WT} = \left( \frac{a}{b} \right) N_{WT}$$

$$a = 8.7 \times 10^5($ / $w)$$

$$b = 621$$

$$c = 700($ / $w)$$

Using (15) and (16), the investment cost of separate UPQC and WECS and also coupled UPQC and WECS can be estimated. Table 3 shows investment costs of separate and coupled configurations for three different ratings. Economic savings due to using coupled configuration compared to separate UPQC and WECS can be seen in Table 3. These results show the proposed configuration has 17.6% up to 20.7% economic saving depending on different ratings.

CONCLUSION

This study compares the coupled operation of the unified power quality conditioner (UPQC) and wind power...
Table 3: Comparison of investment cost and economic saving of separate and coupled UPQC and wind energy system

<table>
<thead>
<tr>
<th>Rating equipment</th>
<th>15 KVA Separate</th>
<th>15 KVA Coupled</th>
<th>150 KVA Separate</th>
<th>150 KVA Coupled</th>
<th>1500 KVA Separate</th>
<th>1500 KVA Coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine</td>
<td>10515</td>
<td>10515</td>
<td>105004</td>
<td>105004</td>
<td>1050000</td>
<td>1050000</td>
</tr>
<tr>
<td>PWM Rectifier</td>
<td>5786</td>
<td>5786</td>
<td>47800</td>
<td>47800</td>
<td>47800</td>
<td>47800</td>
</tr>
<tr>
<td>Grid Side Inverter</td>
<td>5786</td>
<td>-</td>
<td>47800</td>
<td>-</td>
<td>394841</td>
<td>-</td>
</tr>
<tr>
<td>Shunt Inverter</td>
<td>5786</td>
<td>5786</td>
<td>47800</td>
<td>47800</td>
<td>394841</td>
<td>394841</td>
</tr>
<tr>
<td>Series Inverter</td>
<td>5786</td>
<td>5786</td>
<td>47800</td>
<td>47800</td>
<td>394841</td>
<td>394841</td>
</tr>
<tr>
<td>Whole</td>
<td>33662</td>
<td>27876</td>
<td>296202</td>
<td>248702</td>
<td>2629366</td>
<td>2234525</td>
</tr>
<tr>
<td>Economic saving</td>
<td>20.7%</td>
<td>19.1%</td>
<td>17.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

power generation system with decoupled operation of them. The VA rating of series and shunt inverters of UPQC are estimated for both coupled and decoupled systems. Due to providing series inverter's required active power to series compensation through shunt inverter in traditional UPQC, by installing DG on DC link of UPQC and supplying active power required for series compensation by DG, the active power of DG can flow to grid through shunt inverter without any change in its capacity. The investment cost of coupled system is compared with investment cost of decoupled use of UPQC and WECS using the VA rating calculations. The analysis show that coupled operation of UPQC with WECS is significantly economical and the economic saving due to use of decoupled system is estimated nearly 20%.

REFERENCES