Research Journal of Applied Sciences, Engineering and Technology 3(9): 963-967, 2011
ISSN: 2040-7467

Submitted: July 28, 2011 Accepted: September 08, 2011 Published: September 20, 2011

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

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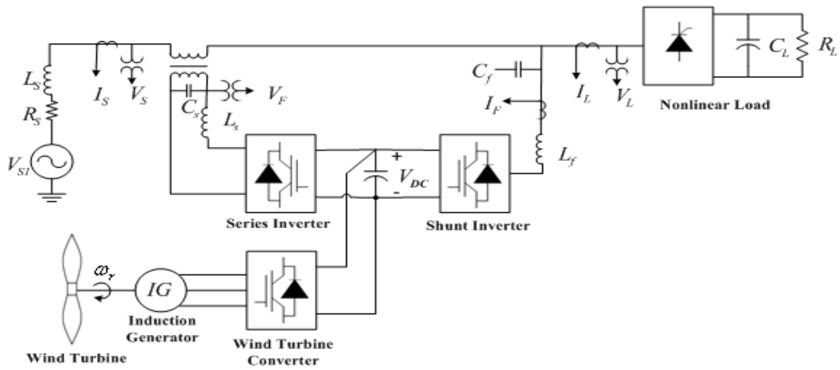

Fig. 1: Configuration of coupled operation of UPQC with WECS

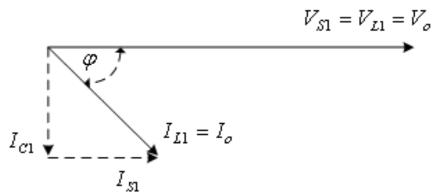

Fig. 2: Phasor diagram of shunt inverter of UPQC

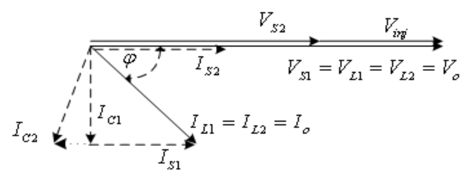

Fig. 3: Phasor diagram of shunt and series inverter of UPQC

compared. To reach this aim, the VA rating of series and shunt inverters of UPQC are estimated. Then the investment cost of coupled system is compared with investment cost of decoupled use of UPQC and WECS using the VA rating calculations. Finally the economic saving due to use of coupled system is estimated.

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; $V_S = V_{LI} = V_{SI} = V_o$ (a constant), and the series injected voltage V_{inj} requirement is zero. This state is represented by adding suffix "1" to all the voltage and current quantities of interest. The load current is $I_{L1}(I_{L1} = I_L)$ and the shunt inverter compensates the reactive component I_{CI} of the load, resulting in unity input power factor. Thus, the current drawn by the shunt inverter is $-I_{CI}$, which is opposite to the load reactive current I_{CI}. As a result, the load always draws the in-phase component I_{SI} 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.

Figure 3 shows phasor diagram of shunt and series inverter of UPQC for fundamental power frequency when the supply voltage sags and UPQC injects V_{ijn} to maintain the load voltage at its desired level (Basu, 2007).

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_{CI} 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_{SI}, and is in phase with V_{S2}.If the active power demand is constant,

$$V_{SI}\ I_{SI=}\ V_{S2}\ I_{S2} \tag{1}$$

which can be written as:

$$I_{S2} = \frac{V_{S1} I_{S1}}{V_{S2}} \tag{2}$$

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:

$$V_S = V_{LI} = V_{L2} = V_{S1} = V_0 \text{ P.U} = \text{vl} \tag{3}$$

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

$$I_L = I_{L1} = I_{L2} = I_0 \text{ P.U} \tag{4}$$

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

$$V_S I_S = V_L I_L \cos\varphi \tag{5}$$

In case of a sag when $V_{S2}<V_{S1}$, where x denotes the p.u. sag,

$$V_{S2} = (1-x)V_{S1} = V_o(1-x)\ P.u \tag{6}$$

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

$$I_{S2} = \frac{V_{S1} I_L \cos\varphi}{V_{S1}(1-x)} = \frac{I_o \cos\varphi}{1-x}\ p.u \tag{7}$$

therefore series inverter VA rating equals to:

$$S_{seinv.} = V_{inj} I_{s2} \frac{V_o I_o (x\cos\varphi)}{1-x}\ p.u \tag{8}$$

Injected current through shunt inverter is:

$$I_{C2} = \sqrt{I_{LI}^2 + I_{SI}^2 = 2 I_{L1} I_{S2} \cos\varphi} = I_o \frac{\sqrt{(1-x)^2 + \cos^2\varphi\{1-2(1-x)\}}}{1-x} \tag{9}$$

therefore shunt inverter VA rating equals to:

$$S_{shinv.} = V_o I_o \frac{1}{1-x}\sqrt{(1-x)^2 + \cos^2\varphi\{1-2(1-x)\}} + I_o^2 \frac{(1-x)^2 + \cos\varphi\{1-2(1-x)\}}{(1-x)^2} Z_{sh.}\ p.u \tag{10}$$

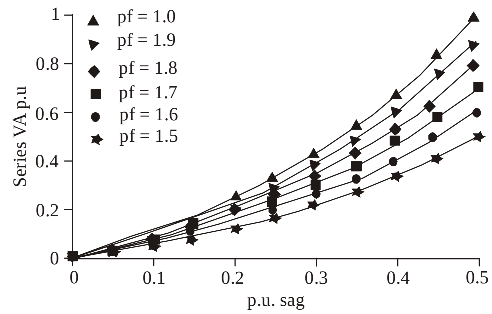

Fig. 4: VA loading of series inverter of UPQC for different power factor and p.u voltage sag values

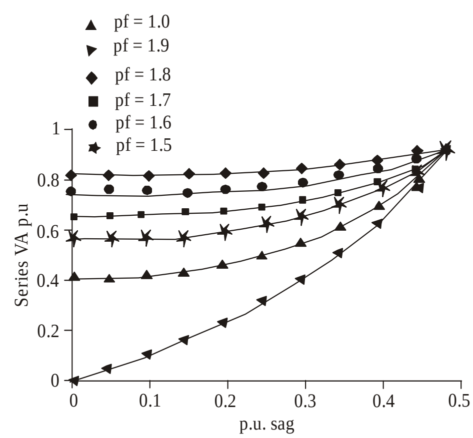

Fig. 5: VA loading of shunt inverter of UPQC for different power factor and p.u voltage sag values

Figure 4-5 show VA loading of series and shunt inverters of UPQC for a wide range of power factor and supply voltage sag variations. The VA loading of inverters is calculated for occurrence of supply voltage sag from 10% to 50% and power factor variations from 0.6 lagging to unity power factor, with Z_{sh} = 0.01 p.u- in all cases. The range of supply voltage sag has been chosen such that most practical cases are observed to be in this range as available from power quality survey reports. The maximum loading within the operating zone would determine the rating of the individual inverter, and the summation of the two would yield the total rating of the UPQC.

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 I_{SI} whose vector sum with I_{CI} will yield I_{C2}. That would be active current in the direction of I_{SI} and its rms value is I_{SE} - C_2 which is equal to vector difference of I_{CI} and I_{C2}:

$$I_{SE\_C2} = \sqrt{I_{c2}^2 - I_{c1}^2} \tag{11}$$

From fig. 8 it can be found that:

$$I_{C1} = I_o \sin\varphi \tag{12}$$

By substituting I_{CI} and I_{C2} from (34) and (31) respectively, I_{SE} –$C_2$is equals to:

$$I_{SE-c2}^2 = I_o^2 \frac{(1-x)^2 + \cos^2\varphi\{1-2(1-x)\}}{(1-x)^2} - I_o^2 \sin^2\varphi \tag{13}$$

Simplifying (13) results in:

$$I_{SE-C2} = I_o \frac{x\cos\varphi}{1-x}\ p.u \tag{14}$$

Assuming, I_o= 1 p.u the value of I_{SE} - C_2 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 thr grid without any change in the capacity of series and shunt inverters.

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 IC_{elec} can be expressed as (Kaldellis and Kavadias, 2007):

Table 1: p.u active current flow in shunt inverter for series compensation for various $\cos\varphi$ and voltage sags

cos φ/ p.u Sag	0.1	0.2	0.3	0.4	0.5
0.5	0.055	0.125	0.213	0.333	0.50
0.6	0.066	0.150	0.255	0.400	0.60
0.7	0.077	0.175	0.300	0.533	0.80
0.8	0.088	0.200	0.342	0.533	0.80
0.9	0.099	0.225	0.385	0.600	0.90
1.0	0.110	0.250	0.428	0.667	1.00

Table 2: Capability of shunt inverter to transmission of active and reactive current for different power factors

cos φ	0.5	0.6	0.7	0.8	0.9	1.0
I_{CI}	0.86	0.8	0.71	0.6	0.43	0.0
I_{DG}-C_2	0.5	0.6	0.7	0.8	0.9	1.0

$$\begin{aligned} IC_{elec} &= \lambda N_p^{1-t} \\ \lambda &= 483(\$/kw) \\ t &= 0.08. \end{aligned} \tag{15}$$

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):

$$\begin{aligned} IC_{WT} &= \left(\frac{a}{b+N_{WT}^x}\right) N_{WT} \\ a &= 8.7 \times 105(\$/kw) \\ b &= 621 \\ c &= 700(\$/kw) \\ x &= 2.05 \end{aligned} \tag{16}$$

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

Table 3: Comparison of investment cost and economic saving of separate and coupled UPQC and wind energy system

	15 KVA		150 KVA		1500 KVA	
Rating equipment	Separate	Coupled	Separate	Coupled	Separate	Coupled
Wind Turbine	10515	10515	105004	105004	1050000	1050000
Pwm Rectifier	5786	5786	47800	478003	94841	394841
Grid Side Inverter	5786	-	47800	-	394841	-
Shunt Inverter	5786	5786	47800	47800	394841	394841
Series Inverter	5786	5786	47800	47800	394841	394841
Whole	33662	27876	296202	248702	2629366	2234525
Economic saving	20.7%		19.1%		17.6%	

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%.

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