Evaluation of Reactive Power Support Capability of Wind Turbines

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Abstract—**Reactive power plays an important role in the operation of power systems, especially in the case of wind energy integration. This paper aims to evaluate the reactive power support capability of wind turbines in both normal and voltage sag conditions. The three 2MW wind turbines studied are a fixed speed wind turbine and two variable speed wind turbines with full-scale and power-scale power converters. Comparison results indicate that at normal operation, the fixed speed wind turbine with a static synchronous compensator is able to consume the highest reactive power, while the variable speed wind turbine with full-scale power converter can supply the highest reactive power. In case of low voltage, the fixed speed wind turbine with the static synchronous compensator can support the highest reactive power if the static synchronous compensator's capacity is similar to the wind turbine's capacity, while if its capacity is equal to 25% of the generator's capacity, the variable speed wind turbine with full-scale power converter has the best performance.**

Keywords-capacitor bank; statcom; reactive power capability; voltage sag; wind turbines

I. INTRODUCTION

Renewable energy resources have attracted great interest and are exploited in many countries. Many wind farms have been connected to power grids contributing significant electric energy yields to their demands. Integrating a wind farm into the power system has a negative impact on its voltage profile [1]. Active power generated from wind farms is not smooth, while the voltage drop on the connected lines depends proportionally on it and hence, voltage at nodes of the power system varies, no matter of the constant voltage control at the terminal of the wind farm. In order to reduce this impact, the reactive power on the grid should also vary inversely and compensate the active power's variation, adjusting the wind farm's reactive power. Additionally, the power system requires from the wind farm to generate or receive a reactive power quantity to support the voltage control at nodes of the power system, or to reduce power loss on the grid [2-6]. However, the reactive power exchange capability of a wind farm depends on the type of the installed wind turbines and the power system operator should know this characteristic in order to request reasonable reactive power quantities.

In general, there are three kinds of wind turbines: Fixed Speed Wind Turbines (FSWT), Variable Speed Wind Turbine with Partial-scale power Converter (PC-VSWT) and Variable Speed Wind Turbine with Full-scale power Converter (FC-VSWT) [7]. Many researches have been conducted solely on the reactive power capabilities of these wind turbines [8-10]. It can be noted that the VSWT can adjust reactive power exchange with the grid by the power converter, while FSWT always receives reactive power from the grid, as it is not equipped with a power converter. To overcome this disadvantage, a capacitor bank or a Static Synchronous Compensator (STATCOM) is suggested for FSWT [11], in order to supply reactive power to the grid. However, the reactive power support capability of an FSWT equipped with reactive power compensation equipment has not yet been compared to other wind turbines' capabilities, especially in the case of low voltage.

This paper evaluates the reactive power capability of wind turbines during operation in two modes: normal operation and voltage sag. The wind turbines considered in this research are PC-VSWT, FC-VSWT, FSWT with capacitor bank and FSWT with STATCOM. This study points out which kinds of wind turbines should be utilized from the perspective of reactive power support capability and can help power system operators to determine the reactive power quantities, which wind farms can support.

II. WIND TURBINE SYSTEM

In general, a wind turbine system consists of a wind turbine, a generator and a shaft-gearbox system, which connects the wind turbine and the generator transferring mechanical power. Depending on the kind of generators used, no, full, or partial-scale power converter is required.

A. FSWT

This wind turbine uses a Squirrel Cage Induction Generator (SCIG) and can be connected to the grid without using a power converter [12]. It has poor controllability in both active and reactive power and during operation it always receives reactive power from the connected grid. Hence, FSWT is often equipped with compensating equipment, such as a capacitor bank [11] or a STATCOM [11, 13]. The configuration of FSWT with capacitor bank or STATCOM is shown in Figure 1.

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B. FC-VSWT

This turbine is equipped with a permanent synchronous generator (PMSG) and its stator is connected to the grid via a full-scale power converter, as shown in Figure 1(c) [12, 14, 15]. During operation, the generated power is transferred through this converter and the converter's capacity is at least equal to the generator's, providing good performance control.

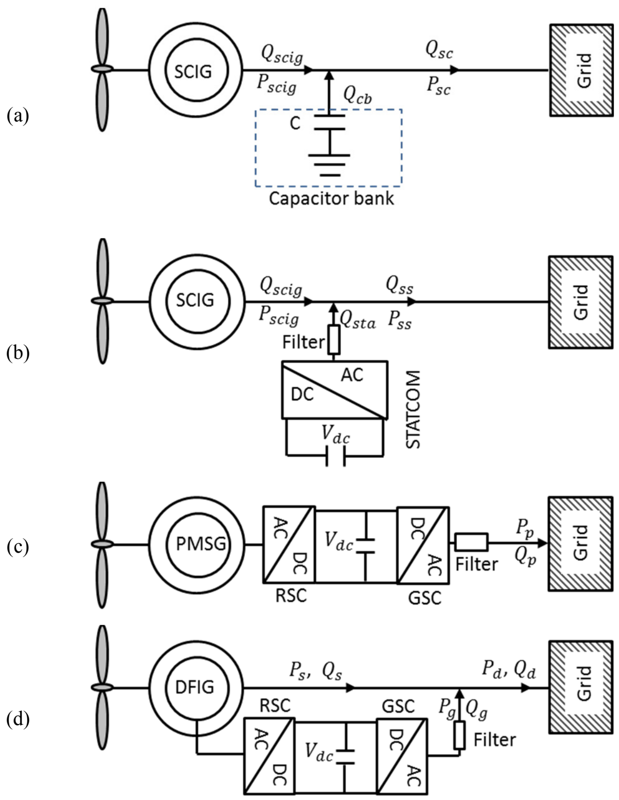

Fig. 1. Wind turbine configuration: (a) FSWT with capacitor bank, (b) FSWT with STATCOM, (c) FC-VSWT, (d) PC-VSWT

C. PC-VSWT

This wind turbine is equipped with a doubly-fed induction generator (DFIG) and it is well-known as the DFIG-wind turbine [12]. A partial-scale power converter is installed at the rotor side, while its stator winding can be directly connected to the grid, as shown in Figure 1d [16-18]. The slip range of DFIG is between 25% and -25%, so the capacity of converter is about 25% of the generator's rating. Via this converter, PC-VSWT has a good controllability. Hence, PC-VSWT can adjust the reactive power flow so that it can supply or absorb reactive power from the grid.

III. REACTIVE POWER ABILITY

A. FSWT

The equivalent circuit of an SCIG can be seen in [12]. X is reactance, R is resistance, i is current, v is voltage, s is the slip of SCIG and subscriptions r, s, m and $scig$ stand for the rotor side, stator side, magnetizing core, and generator. Active power generated by SCIG, P_{scig}, is given by [12]:

$$P_{scig} = \frac{s v_s^2 R_r}{R_r^2 + s^2 X^2} \quad (1)$$

where $X = X_r + X_s$.

Reactive power generated by SCIG, Q_{scig}, is given by:

$$Q_{scig} = \frac{s^2 v_s^2 X}{R_r^2 + s^2 X^2} + \frac{v_s^2}{X_m} \quad (2)$$

From (1) and (2), we have:

$$Q_{scig} = \frac{-v_s^2 R_r + \sqrt{\left(v_s^2 R_r\right)^2 - 4\left(P_{scig} X R_r\right)^2}}{2 X R_r} - \frac{v_s^2}{X_m} \quad (3)$$

hence,

$$\left(Q_{scig} + v_s^2\left(\frac{1}{2X} + \frac{1}{X_m}\right)\right)^2 + P_{scig}^2 = \left(\frac{v_s^2}{2X}\right)^2 \quad (4)$$

For any given value of P_{scig}, Q_{scig} is always negative. FSWT always receives reactive power from the connected grid. In order to reduce the reactive power quantity flowing from the grid, compensating equipment must be installed at SCIG's terminal. Two types of compensating equipment are considered: capacitor bank and STATCOM.

1) FSWT with a Capacitor Bank

Installing a capacitor bank at the terminal of FSWT, generates reactive power as:

$$Q_{cb} = C \omega v_s^2 \quad (5)$$

where, C is the capacitance of the capacitor bank and ω is angular frequency. The real and reactive power quantities exchanged with the connected grid, are computed by:

$$P_{sc} = P_{scig} \quad (6)$$

$$Q_{sc} = Q_{scig} + Q_{cb} = \frac{-v_s^2 + \sqrt{v_s^4 - 4(P_{sc} X)^2}}{2X} - \frac{v_s^2}{X_m} + C \omega v_s^2 \quad (7)$$

Equation (7) indicates that at a constant active power P_{sc}, the reactive power, Q_{sc}, exchanged with the grid is constant. Reactive power depends on the capacitance of the capacitor bank C and if capacitance is high enough, reactive power Q_{sc} can be positive.

2) FSWT with STATCOM

When a STATCOM is installed at the terminal of an FSWT, the reactive power flowing to the connected grid is the sum of the reactive power from SCIG and STATCOM. The STATCOM configuration is shown in Figure 2 and its reactive power is limited by:

$$P_{sta}^2 + Q_{sta}^2 \le (i_{sta,r} v_i)^2 = (m_a \frac{v_{dc}}{2} i_{sta,r})^2 \quad (8)$$

where, P_{sta} and Q_{sta} are active and reactive power from STATCOM, v_i is the voltage at the STATCOM terminal, $i_{sta,r}$ and m_a are the rated current of STATCOM and the modulation index of its controller, respectively.

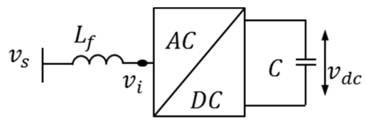

Fig. 2. STATCOM configuration

Remaining at a constant DC voltage v_{dc}, the capacity of STATCOM will limit its reactive power capability as:

$$P_{sta}^2 + Q_{sta}^2 \le (m_a \frac{v_{dc}}{2} i_{sta,r})^2 = (S_{sta,r})^2 \quad (9)$$

where $S_{sta,r}$ is the rated capacity of STATCOM. Moreover, the limitation of power transmission from STATCOM's terminal to the connection point is described as:

$$P_{sta}^2 + (Q_{sta} + \frac{v_s^2}{X_f})^2 \le (\frac{v_i v_s}{X_f})^2 = (m_a \frac{v_{dc} v_s}{2X_f})^2 \quad (10)$$

where $X_f = \omega L_f$ is the reactance of the filter at STATCOM and v_s is the voltage at the connected point. Here, v_{dc} depends on the active power, P_{sta}, supplied from the connected grid. Normally, the active power P_{sta} is almost insignificant. If $v_s \neq 0$, the active power from FSWT or the connected grid is able to keep v_{dc} at a constant value. Here, it is supposed that $P_{sta} \approx 0$. In this case, (9) and (10) become:

$$-S_{sta,r} \le Q_{sta} \le S_{sta,r} \quad (11)$$

$$-\frac{v_s^2}{X_f} - m_a \frac{v_{dc} v_s}{2X_f} \le Q_{sta} \le -\frac{v_s^2}{X_f} + m_a \frac{v_{dc} v_s}{2X_f} \quad (12)$$

and reactive power generated by STATCOM is limited as:

$$A_{sta} \le Q_{sta} \le B_{sta} \quad (13)$$

where:

$$A_{sta} = max\{-\frac{v_s^2}{X_f} - m_a \frac{v_{dc} v_s}{2X_f}, -S_{sta,r}\} \quad (14)$$

$$B_{sta} = min\{-\frac{v_s^2}{X_f} + m_a \frac{v_{dc} v_s}{2X_f}, S_{sta,r}\} \quad (15)$$

Hence, from (3) and (13), the power transmitted from FSWT with STATCOM to the connected line, Q_{ss}, is:

$$P_{ss} = P_{scig} \quad (17)$$

$$Q_{ss} = Q_{scig} + Q_{sta} \quad (18)$$

and the reactive power is limited by

$$Q_{ssmin} \le Q_{ss} \le Q_{ssmax} \quad (19)$$

where,

$$Q_{ssmax} = B_{sta} + \frac{-v_s^2 + \sqrt{v_s^4 - 4(P_{ss}X)^2}}{2X} - \frac{v_s^2}{X_m} \quad (20)$$

$$Q_{ssmin} = A_{sta} + \frac{-v_s^2 + \sqrt{v_s^4 - 4(P_{ss}X)^2}}{2X} - \frac{v_s^2}{X_m} \quad (21)$$

B. FC-VSWT

Reactive power supplied to the grid by FC-VSWT must be limited by the rated capacity of the converter:

$$P_p^2 + Q_p^2 \le S_{g,r}^2 \quad (22)$$

where, $S_{g,r}$ is the rated current capacity of the grid side converter (GSC). Moreover, reactive power depends on the transmitting capability of the filter installed at the terminal of GSC [10]:

$$P_p^2 + (Q_p + \frac{v_g^2}{X_f})^2 \le (\frac{v_i v_g}{X_f})^2 = (m_a \frac{v_{dc} v_g}{2X_f})^2 \quad (23)$$

where X_f is the reactance of the filter at GSC terminal, m_a is the modulation index of its controller, and v_{dc}, v_i and v_g are voltages at DC–link, GSC terminal and the connected grid respectively. From (22) and (23), the reactive power capability of FC-VSWT is limited by:

$$Q_{p,min} \le Q_p \le Q_{p,max} \quad (24)$$

where,

$$Q_{p,max} = min(S_{g,r}, \sqrt{(m_a \frac{v_{dc} v_g}{2X_f})^2 - P_p^2} - \frac{v_g^2}{X_f}) \quad (25)$$

$$Q_{p,min} = max(-S_{g,r}, -\sqrt{(m_a \frac{v_{dc} v_g}{2X_f})^2 - P_p^2} - \frac{v_g^2}{X_f}) \quad (26)$$

C. PC-VSWT

In PC-VSWT, the power exchange with the connected grid is the sum of power on the stator side and the GSC. The power output on the stator side is limited by both the stator winding's rated current $i_{s,r}$ and the rotor winding's rated current $i_{r,r}$, whereas the power in the grid side depends on the capacity of GSC, $S_{g,r}$ and the transmitting capability of the filter installed on GSC [9]:

$$P_s^2 + Q_s^2 \le (i_{s,r} v_s)^2 \quad (27)$$

$$P_s^2 + (Q_s + \frac{v_s^2}{X_s})^2 \le (v_s \frac{X_m i_{r,r}}{X_s})^2 \quad (28)$$

$$P_g^2 + Q_g^2 \le S_{g,r}^2 \quad (29)$$

$$P_g^2 + (Q_g + \frac{v_s^2}{X_f})^2 \le (m_a \frac{v_{dc} v_s}{2X_f})^2 \quad (30)$$

where, P_s and Q_s are the active and reactive power in the stator side, P_g and Q_g are the active and reactive power in GSC, v_s and v_{dc} are the voltages on the stator side and the DC-link, m_a is the modulation index of the controller applied to GSC, and X_s, X_m and X_f are the reactance of stator winding, magnetizing of DFIG and the GSC filter respectively. These can be summarized as:

$$Q_{s,min} \le Q_s \le Q_{s,max} \quad (31)$$

$$Q_{g,min} \le Q_g \le Q_{g,max} \quad (32)$$

where:

$$Q_{s,min} = max(-A_s, -B_s), \; Q_{s,max} = min(A_s, B_s) \quad (33)$$

$$A_s = \sqrt{(i_{s,r} v_s)^2 - P_s^2}, \; B_s = \sqrt{(\frac{X_m v_s i_{r,r}}{X_s})^2 - P_s^2} - \frac{v_s^2}{X_s} \quad (34)$$

$$Q_{g,min} = max(-A_g, -B_g), \quad Q_{g,max} = min(A_g, B_g) \quad (35)$$

$$A_g = \sqrt{S_{g,r}^2 - P_g^2}, \; B_g = \sqrt{(m_a \frac{v_{dc} v_s}{2X_f})^2 - P_g^2} - \frac{v_s^2}{X_f} \quad (36)$$

Reactive power Q_d and active power P_d exchanged with the connected grid are:

$$P_d = P_s + P_g \qquad (37)$$

$$Q_d = Q_s + Q_g \qquad (38)$$

Hence, from (27) to (38), the reactive power exchanged with the grid is limited by:

$$Q_{d,min} \leq Q_d \leq Q_{d,max} \qquad (39)$$

where:

$$Q_{p,max} = Q_{s,min} + Q_{g,min} \qquad (40)$$

$$Q_{p,min} = Q_{s,max} + Q_{g,max} \qquad (41)$$

IV. COMPARISON OF REACTIVE POWER CAPABILITY

In order to obtain this objective, 2MW wind turbines are examined with output voltage at 690V/60Hz (Table I). It is supposed that the capacitor bank of FSWT can generate 2MVAr, so that in normal operation:

$$C = 6.4mF \text{ or } Q_{cb} = \sqrt{3}C\omega v_s^2 = 2MVAr$$

so that it can generate a unity power factor at the rated active power. In STATCOM installation, its capacity is 2MVAr and the reactance of its filter, X_f, is 41.2mΩ.

TABLE I. WIND TURBINES' PARAMETERS [19-21]

Parameter's name	PC-VSWT	FSWT	FC-VSWT
Generator's stator reactance X_s	78,3mΩ	54,9mΩ	
Generator's rotor reactance X_r	32.7mΩ	78.2mΩ	
Generator's magnetizing reactance X_m	1.8935Ω	1.74Ω	
Filter's reactance X_f	12mΩ		41.2mΩ
DC-link voltage	1380V		1380V
GSC's capacity	0.5MVA		2.2MVA

In order to obtain the reactive power capability of each wind turbine, the limitation curves of the reactive power for each wind turbine were plotted in Matlab, using data from (6)-(41) and Table I.

A. Normal Operation

In normal operation, the voltage on the connected grid's terminal is rated at 690V. The reactive power capability of each wind turbine is shown in Figure 3. In general, the reactive power depends on the active power output of the generator. Figure 3(a) indicates that in normal operation, FSWT (SCIG) always receives the reactive power from the grid and its quantity depends on the active power. The higher the active power output is, the higher reactive power is consumed. In the case of a 2MVAr capacitor bank installation, FSWT supplies reactive power to the connected grid. However, at a given active power, it only generates constant reactive power, indicating the lack of adjusting ability. The use of STATCOM increases FSWT's performance in reactive power adjustment, as it can supply or absorb reactive power. The quantity of the exchanged reactive power is limited by the curves *ab* and *cd* in Figure 3(b). FSWT with STATCOM is able to receive more reactive power than it can supply to the grid and its consumption range is always larger than its generation range. Moreover, the lower the active power output is, the lower reactive power can be consumed, but the higher reactive power can be generated. In comparison with the capacitor bank case, the adjustable area of FSWT with STATCOM is larger. Both the GSC and the filter's capacity limit the reactive power exchanged between FC-VSWT and the connected grid. Its adjustable area is *abcde* in Figure 3(c). If its active power output is over 1MW, its reactive power consumption ability is the same as its generation ability and it can supply maximum 2MVAr, while it can consume more.

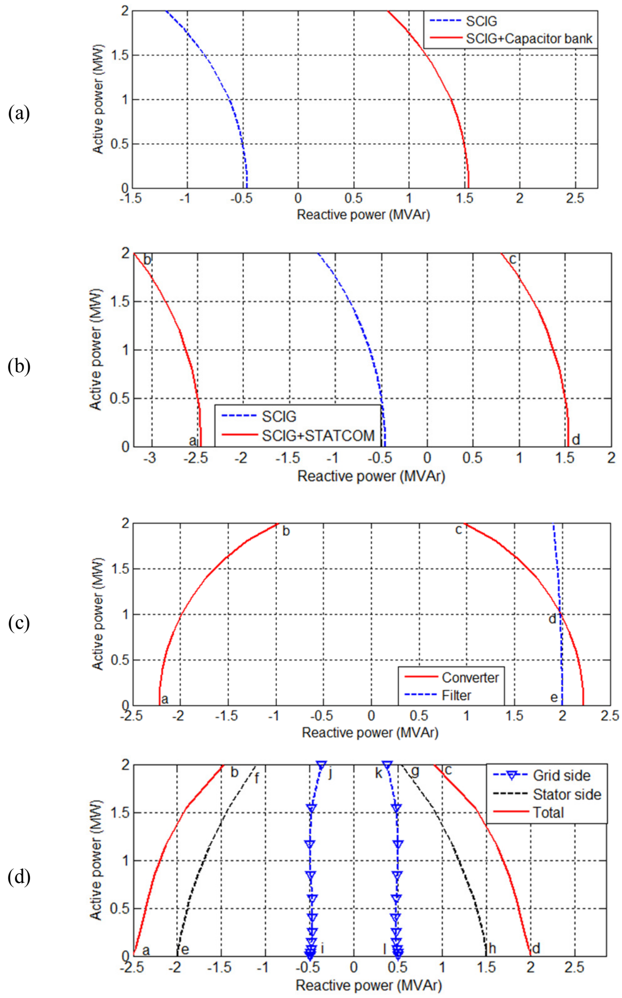

Fig. 3. Reactive power support capability in normal operation: (a) FSWT-capacitor bank, (b) FSWT-STATCOM, (c) FC-VSWT, (d) PC-VSWT

Unlike FC-VSWT, PC-VSWT can supply or receive reactive power from both the stator and the converter's grid side. As a result, the adjustable area of PC-VSWT is *abcd*, which is the sum of the stator side's adjustable area *efgh* and the GSC's area *ijkl* in Figure 3(d). The connected grid can require PC-VSWT either to support or to absorb reactive power within a wide range. However, at constant active power generation, the reactive power consumption range is always larger than the generation range. FSWT with a capacitor bank cannot adjust reactive power but FSWT with a STATCOM can provide reactive power control ability, similar to PC-VSWT or FC-VSWT. Comparing to variable speed wind turbines, the reactive power consumption capability of FSWT with a STATCOM is the best but its reactive power generation capability is the poorest. In variable speed wind turbines, FC-VSWT's reactive power generation is better but its consumption ability is worse than PC-VSWT. In other words, during normal operation, in order to ensure the utilization of electrical energy from wind turbines, power system operators should request FSWT with STATCOM to consume reactive power, while they should request FC-VSWT to supply reactive power, especially in the case of low wind power.

B. Voltage sag

In this section, it is supposed that the voltage at the connection point is reduced by 20%, 40%, 60%, and 80% of the rated value. In the case of PC-VSWT, it is supposed that its crowbar will be activated as the stator voltage is below 70% of the rated value. In this case, the crowbar's resistance of $11R_r$ is added to the rotor winding, whereas GSC plays the role of STATCOM. This means that PC-VSWT becomes an FSWT with a STATCOM. The reactive power versus active power curves are shown in Figure 4. As it can be noted, the lower the voltage, the smaller the maximum active power output is. The active power cannot be transmitted to the connected grid in case of low voltage. The reactive power exchange capability is also reduced during voltage reduction. For FSWT, the voltage reduction makes the P versus Q curve move to the zero point, as it is shown in Figure 4(a). Hence, in the case of an FSWT with a capacitor bank installed, the reactive power supply to the grid is reduced, as shown in Figure 4(b), as the reactive power generated by the capacitor bank is proportional to its terminal voltage square. However, in an FSWT with a STATCOM installed, the lower the voltage, the higher the reactive power supply capability is, as shown in Figure 4(c). At 20% of the rated voltage, FSWT with STATCOM can supply approximately 2MVAr.

The reactive power support capability of FC-VSWT depends heavily on the GSC. As voltage is reduced, its supply capability is reduced and its minimum support capacity is 0.44MVAr for voltage reduced to 20% of the rated value, as shown in Figure 4(d). When voltage is over 70% of the rated value, the reactive power capability of PC-VSWT is reduced sharply, because of the rated rotor current limitation, as shown in (28). At maximum active power generation, the reactive power range is reduced from -1.48 to 0.91MVAr to -0.66 to 0.13MVAr, as the voltage is reduced to 80% of the rated value. When the voltage is below 70% of the rated value, PC-VSWT operates as an FSWT with a 0.5MVAr STATCOM. Hence, if we continue the utilization of active power generation, at 60% of the rated value, the grid must supply reactive power. To support reactive power, PC-VSWT's output should be below 0.8MW and the maximum reactive power at this voltage is 0.35MVAr at 0MW. The lower the voltage, the higher the reactive power support capability is. The highest value of the reactive power is 0.48MVAr, as the voltage is 20% of the rated value.

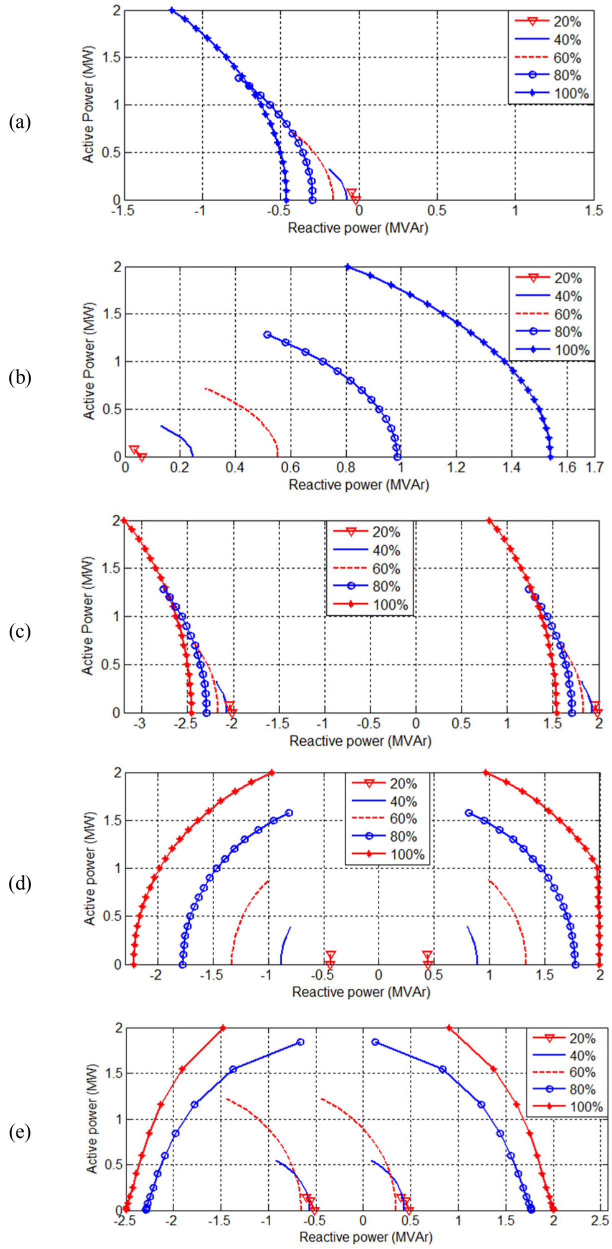

Fig. 4. Reactive power at voltage sag: (a) FSWT, (b) FSWT-capacitor bank, (c) FSWT-STATCOM, (d) FC-VSWT, (e) PC-VSWT

From the above analysis of the considered wind turbines, FSWT with the capacitor bank owns the worst reactive power ability, whereas FSWT with STATCOM can support the highest reactive power to the grid as voltage is lower than 80% of the rated value. Comparing to PC-VSWT, FC-VSWT has better reactive power support capacity if voltage is over 20% of the rated voltage. However, the reactive power support capability of FSWT with STATCOM depends heavily on the STATCOM's capacity. If its capacity is equal to the capacity of the GSC used in PC-VSWT, its support capability cannot be better than PC-VSWT. In general, if STATCOM's capacity in FSWT is similar to the capacity of the converter used in FC-

VSWT, FSWT has the best reactive power support. However, if its capacity is similar to the capacity of the converter used in PC-VSWT, FC-VSWT has the best performance.

V. CONCLUSION

This research studied and compared the reactive power capability of wind turbines in both normal and voltage sag conditions. The results showed that during normal operation, in order to ensure the utilization of the electrical energy from wind turbines, FSWT with STATCOM can absorb the highest reactive power, while FC-VSWT has better capability to supply the reactive power, especially in the case of low wind power. In the case of low voltage, FSWT with a STATCOM installed can support the highest reactive power to the grid if STATCOM's capacity is similar to the wind turbine's capacity, while if its capacity is equal to the capacity of the converter of a PC-VSWT, FC-VSWT has the best reactive power capability.

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