ACTIVE AND REACTIVE POWER DISTRIBUTION AMONG MULTIPLE DFIG WTSS IN AN ISOLATED MICROGRID

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Abstract - Wind energy sector is a well-researched field since depletion of fossil sources and environmental pollution issues led to the popularization of renewables. Many efforts have been made to optimise its power production and to minimize its losses. In case of m different sized power plants, due to different MPPs, if the demand is below the sum of their maximum power production at the given wind speed, it is highly likely that the optimal distribution will not be exact. There are several possibilities, one of them is to share the demand equally among them etc. The distribution of active and reactive powers will have an effect on each other and thus the optimal solution.

Keyword - wind energy, induction generator losses, multiple parallel operating generators, reactive and active power distribution, efficiency

1 INTRODUCTION

The use of wind energy is getting widely spread due to the ever raising popularity of renewable sources. In order to produce more and more power by wind, enormous wind parks are built. However, when connecting multiple wind generators in parallel there are many aspects that have to be examined. Issues regarding to series and parallel connection of wind turbines were compared in [1]. In [2] the produced power was examined of two, different sized wind generators connected together at various wind speeds. Power optimization is the main goal to execute an economical, long-life process thus it is crucial to realize all the losses, occuring in wind power plants. The losses of an 37 kW induction machine were analyzed in [3]. The core and stray load losses were examined in brushless doubly fed induction generators in [4]. In order to minimize the losses of wind generators while maximizing the produced power, several articles presented various maximum power point tracking (MPPT) methods [5], [6].

Doubly-fed induction generator-wind turbine systems (DFIG WTSs) consist of a wind turbine (WT) and a doubly fed induction generator (DFIG). The wind turbine is linked to the generator through a gearbox and shaft system. The DFIG is essentially a wound rotor induction generator in which the rotor voltage can be controlled to achieve variable speed operation. The stator side of the DFIG is often connected directly to the grid through a transformer, whereas the rotor side is connected through a partial converter, including a rotor-side converter (RSC) and a grid-side converter (GSC) and a filter as shown in Figure 1 [7].

In the current paper m parallel connected DFIG WTSs are studied that are utilized in an isolated or autonomous AC microgrid supplying loads in remote areas. The main goal is to utilize all the maximum wind power possible, thus all the DFIG WTSs are operating at their MPPs. However, in case of an isolated microgrid, the active power demand of the grid might be smaller than the sum of the total maximum power of the DFIG WTSs $P^* < \sum_{i=1}^{m} P_{MPP,i}$. The main purpose of this paper is to investigate the optimal distribution of active P^* and reactive Q^* power among m multiple DFIG WTSs. The optimal solution in our case means that the total conversion efficiency is maximal.

As DFIG WTS is a highly nonlinear system, the calculation of the optimal point is a complex mathematical task. For simplicity, later on, let us assume that two ($m = 2$) different DFIG WTSs (denoted by "a" being the smaller, 55 kW and "b", being the bigger, 90 kW generator) supply the isolated microgrid. The outline of this paper will be as follows: Section 2 collects the analytical formulas of a DFIG WTS, Section 3 reveals the loss calculation of these systems and finally, Section 4 introduces a calculation method for optimal active and reactive power distribution. The parameters of both DFIG WTSs [2], rotor side converter (RSC) and grid side converter (GSC) [8] can be found in the Appendix.

2 ANALYTICAL FORMULAS OF A DFIG WTS

DFIG WTS is widely accepted in today's wind energy industry. In order to get the total efficiency of the system both the power of the turbine and the power fed

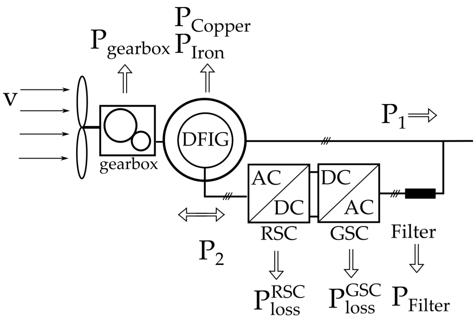

Fig. 1. DFIG WTS in an isolated microgrid

back to the grid needs to be calculated. The turbine power P_{turb}, $[W]$ is influenced by the wind speed, the blade pitch angle and the speed of the turbine as follows:

$$P_{turb} = \rho \cdot \frac{R^2\pi}{2} \cdot v^3 \cdot c_p(\lambda, \beta) \quad (1)$$

where:

$$\lambda = \frac{\omega_{tb} \cdot R}{v} \quad (2)$$

$$c_p(\lambda, \beta) = 0.5(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma} \quad (3)$$

$$\Gamma = \frac{R}{\lambda} \cdot \frac{3600}{1609} \quad (4)$$

ρ is the air density $[kg/m^3]$, R is the radius of the blade $[m]$, v is the actual wind speed $[m/s]$, c_p is the power coefficient, ω_{tb} is the actual speed of the turbine $[rad/s]$, β is the blade pitch angle $[deg]$ and λ is the tip speed ratio $[-]$. Here the power coefficient is calculated based on the assumptions in [2].

Figure 2 presents the turbine power as a function of the turbine speed of a 55 kW wind turbine "a" and 90 kW turbine "b" at their operating wind speed range. The power for a certain v is maximum at a certain value of ω_{tb}. This is the speed which corresponds to the optimum tip speed ratio λ_{opt} at which the turbine should always operate, in order to produce the maximum power possible. This can be done by applying various MPPT control strategies. The most common MPPT techniques for wind energy conversion systems (WECS) are: wind speed measurement, Perturb and Observe (PO) and speed-sensoreless power signal feedback (PSF). Above the rated wind speed range, the turbine maintains constant power output by a pitch system control.

The speed of the turbine determines the actual rotational speed of the generator, n $[rpm]$:

$$n = \omega_{tb} \cdot q \cdot \frac{60}{2\pi} \quad (5)$$

where q is the ratio of the gearbox $[-]$. The slip of the generator can be calculated from n and the synchronous speed, n_1 $[rpm]$ (For a DFIG the slip generally varies between $\pm 30\%$.):

$$s = \frac{n_1 - n}{n_1} \quad (6)$$

The torque, M $[Nm]$ of the generator is calculated from the shaft power:

$$M = \frac{-P_{turb}}{\omega_{tb} \cdot q} \quad (7)$$

Figure 3 shows the equivalent circuit of a DFIG consisting of stator and rotor resistances and inductances and a magnetizing leakage inductance (the iron loss of the generator is neglected in the paper and therefore not shown on the figure).

For the three phase power of the stator side of the generator, the following equation can be written (the voltage and current quantities are RMS values and the quantities are referred to the stator side of the machine):

$$P_1 - P_{C_1} = 3 \cdot \frac{|\boldsymbol{U_1}|}{\sqrt{3}}|\boldsymbol{I_1}|cos\varphi - 3 \cdot |\boldsymbol{I_1}|^2 R_1 = M \cdot \Omega_1 \quad (8)$$

where $cos\varphi$ is the power factor $[-]$, $|\boldsymbol{U_1}|$ is the length of the stator line voltage vector $[V]$, R_1 is the copper resistance on the stator side $[\Omega]$, $|\boldsymbol{I_1}|$ is the size of the stator current vector $[A]$, Ω_1 is the mechanical speed of the machine $[rad/sec]$, P_1 is the stator power $[W]$, P_{C_1} is the copper loss of the stator, $[W]$. The different powers of a DFIG are defined and further explained later in Section 3. By realigning the equation, the size of the stator current vector can be expressed as:

$$|\boldsymbol{I_1}|_{\boldsymbol{1,2}} = \frac{\frac{|\boldsymbol{U_1}|\cdot\cos\varphi}{\sqrt{3}} \pm \sqrt{\left(\frac{|\boldsymbol{U_1}|\cdot\cos\varphi}{\sqrt{3}}\right)^2 - \frac{4\cdot R_1\cdot M\cdot 2\pi\cdot n_1}{3\cdot 60}}}{2 \cdot R_1} \quad (9)$$

The voltage of the magnetizing branch can be calculated as follows:

$$\boldsymbol{U_m} = \frac{|\boldsymbol{U_1}|}{\sqrt{3}} - |\boldsymbol{I_1}|(-\cos\varphi + j\sin\varphi)(R_1 + 2\pi f j L_{l1}) \quad (10)$$

where f is the frequency of the network voltage $[Hz]$, L_{l1} is the leakage inductance of the copper on the stator side $[H]$. $\boldsymbol{U_m}$ determinates the magnetizing line current:

$$\boldsymbol{I_m} = \frac{\boldsymbol{U_m}}{2\pi \cdot f \cdot jL_m} \quad (11)$$

where L_m is the inductance of the magnetizing line $[H]$. Based on the equivalent circuit, the rotor current referred to the stator side can be calculated from $|\boldsymbol{I_1}|$ and $\boldsymbol{I_m}$ as follows:

$$\boldsymbol{I_2} = |\boldsymbol{I_1}| \cdot (-\cos\varphi + j\sin\varphi) - \boldsymbol{I_m} \quad (12)$$

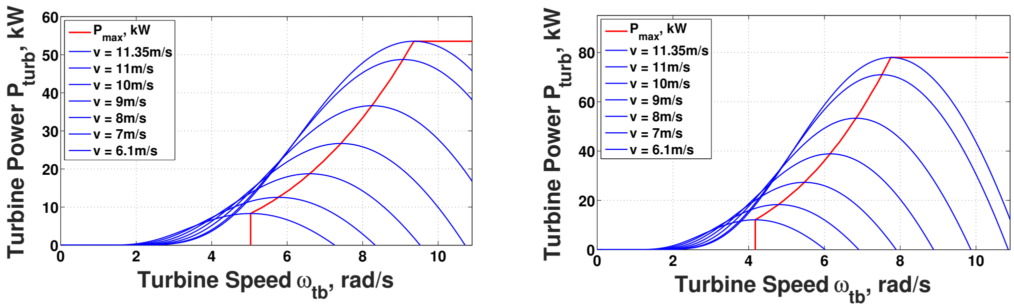

Fig. 2. Turbine power as a function of turbine speed for various wind speeds, DFIG WTS “a” (left), “b” (right)

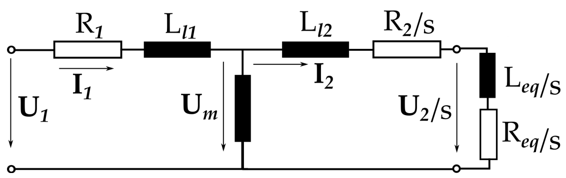

Fig. 3. Equivalent circuit of a DFIG without the iron resistance

The rotor voltage is determined by $\boldsymbol{I_2}$ in the following way:

$$\boldsymbol{U_2} = s \cdot \boldsymbol{U_m} - \boldsymbol{I_2} \cdot (R_2 + 2\pi \cdot f \cdot s \cdot jL_{l2}) \quad (13)$$

where R_2 is the resistance of the copper on the rotor side $[\Omega]$, L_{l2} is the leakage inductance of the copper on the rotor side $[H]$. The RSC can be modelled as an equivalent impedance $[\Omega]$, which can be calculated as:

$$\boldsymbol{Z_{eq}} = \frac{\boldsymbol{U_2}}{\boldsymbol{I_2}} \quad (14)$$

The stator power, P_1 $[W]$ of the generator can be calculated based on the following equation :

$$P_1 = 3 \cdot \cos\varphi \cdot \frac{|\boldsymbol{U_1}|}{\sqrt{3}} \cdot |\boldsymbol{I_1}| \quad (15)$$

The power of the rotor, P_2 $[W]$ can be calculated as the following:

$$P_2 = 3 \cdot |\boldsymbol{I_2}|^2 \cdot Re\{\boldsymbol{Z_{eq}}\} \quad (16)$$

where $|\boldsymbol{I_2}|$ is the length of $\boldsymbol{I_2}$, $Re\{\boldsymbol{Z_{eq}}\}$ represents the real part of $\boldsymbol{Z_{eq}}$. The mechanical power of the induction machine is represented by the next equation:

$$P_{mech} = 3 \cdot |\boldsymbol{I_2}|^2 \cdot (Re\{\boldsymbol{Z_{eq}}\} + R_2) \cdot \frac{1-s}{s} \quad (17)$$

When calculating the amount of power supplied back to the network, two operating modes need to be separated. When $Re\{\boldsymbol{Z_{eq}}\} > 0$, being in supersynchronous mode, the power supplied back to the network, can be calculated from the sum of the stator and the absolute value of rotor power $P = P_1 + |P_2|$. In other cases, when operating in subsynchronous mode, the absolute value of the rotor power needs to be substracted from the stator power, $P = P_1 - |P_2|$. Figure 1 also shows the active power flow of a DFIG WTS. The reactive power, Q $[VAr]$ fed back to the network can be calculated from the active network power and the phase angle, φ $[deg]$ of the machine:

$$Q = P \cdot \tan\varphi \quad (18)$$

The efficiency, η $[-]$ of the DFIG WTS can be calculated by dividing the power of the turbine by the power supplied back to the network:

$$\eta = \frac{P}{P_{turb}} \quad (19)$$

3 Loss Calculation for a DFIG WTS

J. Tamura et al. sums up in [9] the losses that reduce the power produced by the wind from the mechanical side to the electrical conversion for DFIG WTSs:

- Mechanical losses: gearbox losses, windage loss, ball bearing loss
- Copper losses: primary winding copper loss, secondary winding copper loss
- Iron losses: eddy current loss, hysteresis loss
- Stray load loss
- Power converter loss

The losses considered in the calculations of this paper are further explained in the following. Gearbox loss is caused by the contact loss of the tooth and viscous oil and can be calculated in the following way [8]:

$$P_{Gb} = \eta_{gm} \cdot P_l + \xi \cdot P_{turb,n} \cdot \frac{\omega_{tb}}{\omega_{tbn}} \quad (20)$$

where η_{gm} is the gear-mesh constant $[-]$ and ξ is the friction constant $[-]$, P_l is the power of the turbine $[W]$ at the lowest speed limit, $P_{turb,n}$ is the nominal power $[W]$ of the turbine and ω_{tbn} is the nominal speed of the turbine $[rad/sec]$. Copper losses occur in winding coil both on the stator and on the rotor side as follows [9]:

$$P_{Copper} = P_{C_1} + P_{C_2} = 3 \cdot \left(R_1|\boldsymbol{I_1}|^2 + R_2|\boldsymbol{I_2}|^2\right) \quad (21)$$

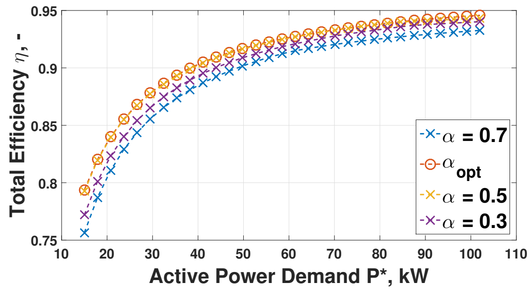

Fig. 4. Total efficiency at different distribution ratios at 11.35 m/s

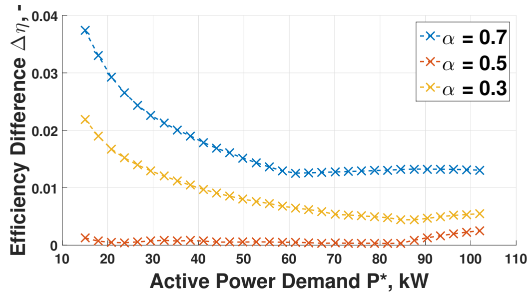

Fig. 5. The difference between optimal efficiency and efficiencies at other distribution ratios

The losses of the converter can be calculated both on the grid and on the generator side from the conduction losses P_c $[W]$, the switching losses of the transistor, $P_{s,t}$ $[W]$ and the inverse diode $P_{s,d}$ $[W]$ as follows [10]:

$$P_c = 3 \cdot \left(U_{IGBT} \cdot \frac{2\sqrt{2}}{\pi} \cdot |\boldsymbol{I_2}| + R_{IGBT} \cdot |\boldsymbol{I_2}|^2 \right) \tag{22}$$

$$P_{s,t} = 3 \cdot \left((E_{on} + E_{off}) \frac{2\sqrt{2}}{\pi} \cdot \frac{|\boldsymbol{I_2}|}{I_{c,nom}} \cdot f_{sw} \right) \tag{23}$$

$$P_{s,d} = 3 \cdot \left(E_{rr} \cdot \frac{2\sqrt{2}}{\pi} \cdot \frac{|\boldsymbol{I_2}|}{I_{c,nom}} \cdot f_{sw} \right) \tag{24}$$

where $U_{IGBT} = U_{ce_0}$ is the voltage of the IGBT $[V]$, which according to [8] can be considered as equal to the voltage of the transistor, while also the resistance of the IGBT, R_{IGBT} $[\Omega]$ can be considered as the lead resistance of the IGBT, R_{ce}. $I_{c,nom}$ $[A]$ is the nominal current of the converter. E_{on} and E_{off} $[J]$ are the turn on and turn off energies of the IGBT respectively, f_{sw} $[Hz]$ is the switching frequency. Using the above collected equations, the total loss of the RSC can be calculated:

$$P_{loss}^{rsc} = P_c + P_{s,t} + P_{s,d} \tag{25}$$

The losses of the GSC can be calculated similarly, however the rotor current needs to be converted to the grid side voltage in the following way for simplicity :

$$I_2^{grid} = \frac{I_2 \cdot U_2}{|\boldsymbol{U_1}|} \tag{26}$$

4 Total Efficiency Optimisation Strategy

The total efficiency calculation was implemented in Matlab R2016a working with `fmincon` function. `Fmincon`, using the sqp algorithm, minimizes a given objective function according to the nonlinear constraints. The inputs of the calculation are wind speed, active and reactive power demand, while also the parameters of each turbine-generator units, gearboxes and converters.

The active power production of each unit is limited by the nominal power of the generators, while the reactive power is limited by the nominal current of the generators. P^* is distributed among the two DFIG WTSs at the actual active power distribution ratio, $\alpha[-]$.

$$\begin{aligned} P_a^* &= \alpha \cdot P^* \\ P_b^* &= (1-\alpha) \cdot P^* \end{aligned} \tag{27}$$

This means that if $\alpha > 0.5$, generator "a", else generator "b" produces more power. The reactive power demand Q^* is also distributed similarly at the actual reactive distribution ratio, $\kappa[-]$.

$$\begin{aligned} Q_a^* &= \kappa \cdot Q^* \\ Q_b^* &= (1-\kappa) \cdot Q^* \end{aligned} \tag{28}$$

The total efficiency can be calculated by multiplying the efficiency of each units:

$$\eta_i = \eta_a \cdot \eta_b \tag{29}$$

The goal of the optimisation is, to minimize $|1 - \eta_i|$, consequently reaching the highest efficiency possible. This can be done by changing the following values of every single machine separately in a restricted range:

- Blade pitch angle, $\beta = [-5; 15]$
- Turbine speed, $\omega_{tb} = [0.7 \cdot \omega_0; 1.3 \cdot \omega_0]$ (set by the slip of the DFIG machines, $s = [-0.3; +0.3]$
- Distribution ratio of the active power $\alpha = [0; 1]$.
- Distribution ratio of the reactive power $\kappa = [0; 1]$.

The initial value of each variable is set as the following: $\beta_0 = 0$, $\omega_0 = \frac{2 \cdot \pi \cdot n_1}{60 \cdot q}$ (which is the turbine speed at synchronous generator speed), $\alpha_0 = 0$, $\kappa_0 = 0$. The following values are constrained during the optimisation process:

- In generating mode the stator power always needs to be smaller than the nominal power of the machine, $P_1 - P_n \leq 0$
- The stator current always needs to be smaller than the nominal current of the machine, $|I_1| - I_n \leq 0$
- The power coefficient cannot be negative, $c_p \geq 0$

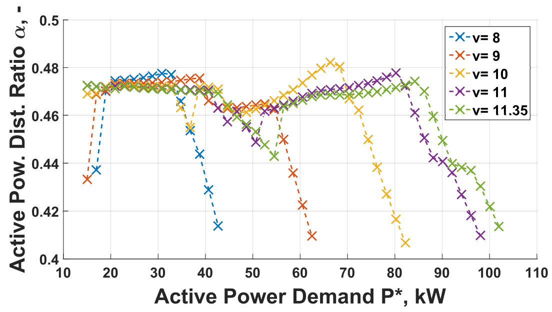

Fig. 6. The optimal active power distribution at different power demands and wind speeds

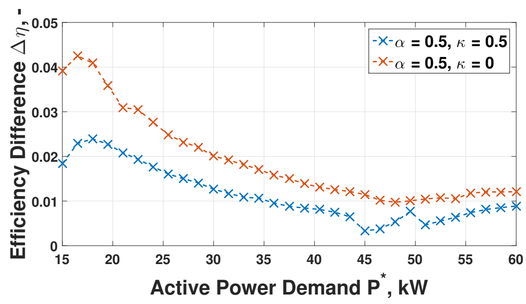

Fig. 8. The difference between optimal efficiency and other efficiencies with κ

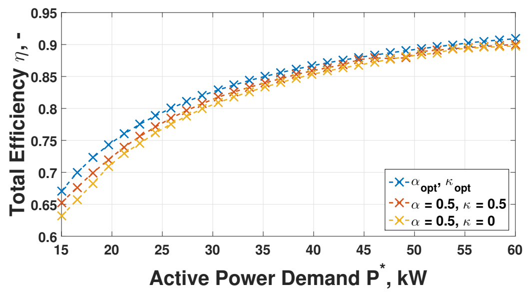

Fig. 7. Efficiencies at different α, κ distribution ratios at 9 m/s

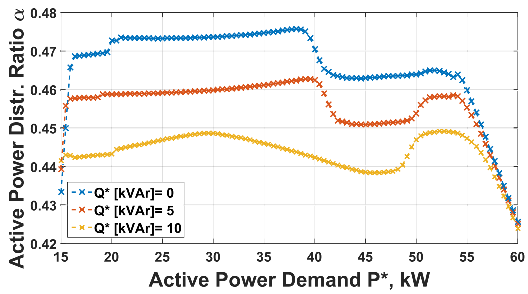

Fig. 9. The effect of reactive power demand on the α distribution ratio

Since both the power fed to the network and the speed of the turbines are unknown quantities, an iteration loop is necessary. Consequently another constraint is set for the function: The produced active network power should be close enough to the demand: $|P - P^*| \leq \varepsilon$. There is no need to constrain Q^* any further, since ε, P and φ are determining that Q is close enough to Q^*.

When operating at higher wind speeds, reaching higher efficiency is possible and so is at higher power demands. On the other hand, at smaller wind speeds, the range of the producable power demand is smaller. The highest possible total efficiency is $\eta_i = 0.95$ at $v = 11.35m/s$, which is the highest operation point.

Figure 4 shows the total efficiency of the system at different distribution ratios, while Figure 5 shows the difference between the optimal efficiency (which is reached at optimal α) and efficiencies at various other ratios, both at a certain power demand range $P^* = [15kW; 102kW]$ at $v = 11.35m/s$ when $Q^* = 0kVAr$. If $\alpha > 0.5$ at every power demand, the efficiency is less than the optimal. On the other hand at $\alpha < 0.5$, the efficiency gets closer to the optimum, because the 90 kW unit produces more power. $\alpha = 0.5$ is the nearest to the optimal efficiency (meaning that the two units share the demand equally among each other). At higher demands however, the optimal distribution ratio is getting further from $\alpha = 0.5$, showing that defining the optimal α can lead to a more efficient power production. Furthermore, as the optimal ratio highly depends on the parameters and rated power of the DFIG, for other machine sets the optimal ratio might be far from 0.5.

Figure 6 shows the chosen α that ensures the highest efficiencies at the above given power demand. It can be seen that at every wind speed the maximum of the operating power range is different. At the lower and higher limits of producable power for every wind speed the optimal distribution ratio is decreasing, meaning that the 90 kW unit produces more power. At a given wind speed, different power demands require different α for the optimum. For example, at $v = 9m/s$, $P^* = 21kW$ power demand, the optimal distribution ratio is $\alpha = 0.473$, however if the demand becomes greater, $P^* = 60kW$ at the same wind speed, $\alpha = 0.422$ is the optimal.

In the following the effect of reactive power distribution on the efficiency is examined, as until now only the active power demand has been shared among the generators. Figure 7 shows that the total efficiency is higher if both α and κ is optimal compared with other ratios when $Q^* = 50kVAr$ and $P^* = [15kW; 60kW]$ at $v = 9m/s$. The efficiency difference between the optimum and other solutions can be seen on Figure 8. On this interval, $\kappa = 0$ is better compared to the case when Q^* is shared equally among the two units. When defining Q^* demand, the optimal α also changed compared to the case of $Q^* = 0VAr$ (Figure 9).

5 Conclusion

This paper examined the question of active and reactive power distribution among two, different sized DFIG WTSs, while optimising the total efficiency of the system. Using the presented method for active power demands, higher efficiency can be reached than by sharing the demand among the two units equally. Defining a reactive power demand as well, resulted in a change of the active power distribution ratio. Further investigations are required in the area, including different WTS configurations In reality, α and κ ratios can be calculated and set by a supervisory control level that makes the decision about the optimal operation point. Future work also consists of deeper examining and explaining the effects of sharing active and reactive power on each other while also implementing $m > 2$ DFIG WTSs to the system.

Acknowledgments

This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

References

[1] M. Liserre, R. Cárdenas, M. Molinas, and J. Rodríguez, "Overview of multi-mw wind turbines and wind parks," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1081–1095, 2011.

[2] P. K. Goel, B. Singh, S. Murthy, and N. Kishore, "Parallel operation of dfigs in three-phase four-wire autonomous wind energy conversion system," *IEEE Transactions on Industry Applications*, vol. 47, no. 4, pp. 1872–1883, 2011.

[3] Lassi Aarniovuori and Paavo Rasilo and Markku Niemelä and Juha J. Pyrhönen, "Analysis of 37-kw converter-fed induction motor losses," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 9, pp. 5357–5365, 2016.

[4] H. Gorginpour, H. Oraee, and E. Abdi, "Calculation of core and stray load losses in brushless doubly fed induction generators," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3167–3177, 2014.

[5] M. C. D. Piazza and M. Pucci, "Induction-machines-based wind generators with neural maximum power point tracking and minimum losses techniques," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 944–955, 2016.

[6] C. Wei, Z. Zhang, W. Qiao, and L. Qu, "Reinforcement-learning-based intelligent maximum power point tracking control for wind energy conversion systems," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 10, pp. 6360–6370, 2015.

[7] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*. John Wiley & Sons, 2011.

[8] A. Petersson, "Analysis, modeling and control of doubly-fed induction generators for wind turbines," Ph.D. dissertation, 2005.

[9] J. Tamura, M. H. Ali, R. Takahashi, T. Murata, M. Kimura, M. Futami, M. Ichinose, and Kazumasa, "A calculation method of the total efficiency of wind generator," in *2005 International Conference on Power Electronics and Drives Systems*, 2005.

[10] B. Zhang, W. Hu, and Z. Chen, "Loss minimizing operation of doubly fed induction generator based wind generation systems considering reactive power provision," in *Industrial Electronics Society, IECON 2014, 40th Annual Conference of the IEEE*, 2014.

7 Appendix

7.1 Parameters of DFIG WTS block "a"

6 Pole DFIG Parameters
$P_n = 55kW; R_1 = 0.02824\Omega; f = 50Hz;$
$R_2 = 0.02439\Omega; U = 415V; L_1 = 0.326mH;$
$L_m = 0.0142mH; L_2 = 0.412mH$
Turbine Parameters
$P_{turb,n} = 55kW; v = (6.1; 11.35)m/s;$
$R = 6.862m;$
Gearbox Parameters
$q = 1 : 14.48; \eta_{gm} = 0.005; \xi = 0.005$

7.2 Parameters of DFIG WTS block "b"

6 Pole DFIG Parameters
$P_n = 90kW; R_1 = 0.03600\Omega; f = 50Hz;$
$R_2 = 0.02439\Omega; U = 690V; L_1 = 0.753mH;$
$L_m = 0.0257mH; L_2 = 0.772mH$
Turbine Parameters
$P_{turb,n} = 80kW; v = (6.1; 11.35)m/s; R = 8.28m$
Gearbox Parameters
$q = 1 : 17.49; \eta_{gm} = 0.005; \xi = 0.005$

7.3 Parameters of both RSC and GSC

$I_{c,nom} = 500A; U_{cc} = 1200V; U_{ce_0} = 1.0V;$
$R_{ce} = 3m\Omega; E_{on} + E_{off} = 288mJ; f_{sw} = 2kHz;$
$E_{rr} = 43mJ;$