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REDUCED COST OF REACTIVE POWER IN DOUBLY FED INDUCTION GENERATOR WIND TURBINE SYSTEM WITH OPTIMIZED GRID FILTER

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Abstract—The modern grid requirement has caused that the wind power system behaves more like conventional rotating generators, and it is able to support certain amount of the reactive power. For a typical doubly fed induction generator (DFIG) wind turbine system, the reactive power can be supported either through the rotor-side converter or the grid-side converter. This paper first compares the current ripples and supportive reactive power ranges between the conventional L and optimized LCL filter, if the reactive power is injected from the grid-side converter. Then, the loss distribution is evaluated both for the generator and the wind power converter in terms of the reactive power done by the rotor-side converter or the grid-side converter with various grid filters. Afterward, the annual energy loss is also estimated based on yearly wind profile. Finally, experimental results of the loss distribution are performed in a down-scaled DFIG system. It is concluded that overexcited reactive power injected from the grid-side converter has lower energy loss per year compared to the overexcited reactive power covered by the rotor-side converter. Furthermore, it is also found that the annual energy loss could even become lower with the optimized filter and thereby more energy production for the wind turbine

I. INTRODUCTION

THE voltage-source converter is widely used as an interface for the renewable energy systems before they are linked to the grid like in the photovoltaic and wind power system cases, with its advantages in fully control of dc-link voltage, active and reactive power, as well as power factor [1]–[3]. A grid filter is normally introduced to avoid the pulse width modulation carrier and side-band voltage harmonics coupling to the grid that can disturb other sensitive loads or equipment. For the megawatt-level wind power converter, due to the quite low switching frequency of the power switching devices (usually several kilohertz), a simple filter inductor consequently becomesIn order to fulfill the modern grid codes . the wind turbine system is currently required to behave more like a traditional power source (e.g., synchronous generator), which implies that the wind turbine system should have the capability of reactive power support. Due to the doubly fed mechanism of the doubly fed induction generator (DFIG)-based wind turbine system, the reactive power can be supported either by the grid-side converter (GSC) or the rotor-side converter (RSC). If the reactive power is provided by the GSC, in the case of the constant dc-link voltage, the modulation index is closely related to the filter inductance, and it will increase very fast to overmodulation, especially when overexcited (OE) reactive power is needed [10]. There are two ways to deal with this issue—increase the dc-link voltage, which gives higher switching loss and power rating, or design an optimized grid filter. Besides, if a small amount of reactive power is demanded by the transmission system operator, it is also of interest to compare the loss of the whole DFIG system, as the reactive power supported by the GSC only affects the loss of the GSC, while the reactive provided by the RSC not only influences the loss of the RSC, but also the loss of the generator itself. Then, the annual energy loss of the wind turbine system and cost of the reactive power can be calculated based on the annual wind profile at different compensation schemesand 2) the absolutevoltage level of a standalone microgrid is moved as the consequence of the heap request variation.A number of marvels influence the batteries operation amid the charging mode [19]: 1) applying high charging streams, the batteries voltages rapidly reach to the gassing threshold;2) the inward resistor and subsequently control misfortunes and warm impacts increment at high SOC levels; and 3) batteries can't befully accused of a steady high charging current.The work in [6] limits, as an operational imperative, the most extreme absorbe influence by the batteries keeping in mind the end goal to

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shield them from being cheated. Nonetheless, since batteries go about as nonlinear burdens amid the charging mode, it doesn't as a matter of course farthest point the chargingcurrents. On the other hand, the works in [10] limits the maximumattainable SOC that prompts unused capacities.Depending on the extent of the force era to theload request proportion inside standalone DC microgrids, three casesare imagined: 1) power era and burden interest are balanced;2) load request surpasses power era causes dc transport voltage to drop without any heap shedding; and 3) powergeneration is higher than burden request drives batteries to be overchargedand transport voltage to climb. This study concentrates on case 3 in which the created power must be shortened on the off chance that it violatesthe batteries charging rates or if batteries are completely charged. A novel vitality administration system (EMS) is proposed to address,as its control goals, three previously mentioned issues comparing standalone dc microgrids; i.e., dc transport voltage regulation,proportional power sharing, and battery administration. Rather than the procedures accessible in writing in which renewableenergy frameworks (RESs) dependably work in their MPPT mode, the proposed multivariable technique utilizes a wind turbine and a PV exhibit as controllable generators and reduces their generationsif it is fundamental. The proposed EMS is produced as an online novel NMPC methodology that persistently takes care of an optimalcontrol issue (OCP) and finds the ideal qualities ofthe pitch point and three exchanging obligation cycles. It all the while controls four variables of microgrids: 1) power coefficientof the wind turbine; 2) rakish speed of the wind generator; 3) working voltage of the PV exhibit; and 4) charging current ofthe battery bank. It is demonstrated that, utilizing new accessible nonlinear advancement procedures and instruments, the computational timeto understand the subsequent NMPC methodology is in passable extent. Dissimilar to dump load-based systems that exclusive secure the batteryfromovercharging, the proposed procedure executes the IU charging administration that expands the batteries life range. Also, evacuating dump stacks, the general establishment expense is reduced.This paper is sorted out as takes after: Section II presentsthe numerical model of standalone dc microgrids. Area III demonstrates the exhibited EMS as an OCP issue which is acknowledged as a NMPC-based procedure. Segment IV presents anddiscusses the got comes about. At long last, the finish of the study is given in Section V.

II. FUNCTIONS OF GRID FILTER

One of the most popular concepts in the mainstream wind power system market is the DFIG configuration as shown in Fig. 1. Except for the advantage that the back-to-back power converters take up only the slip power of the DFIG, this configuration has two possibilities to deliver the demanded reactive

Since this paper focuses on the case in which there is an excess power greater than or equal to the maximum possible absorbing rate of the battery bank, thehybrid nature of the battery bank operation is ignored for the sake of simplicity. The differential and algebraic states, i.e., and , and the manipulated and non-manipulated control variables, namely, and , are detailed later throughout the next sub-sections.
In what follows, the following notations are used to model the standalone dc microgrid in Fig. 1 as DAEs:

$$\mathcal{F}(\mathrm{x}, \dot{\mathrm{x}}, \mathrm{z}, \mathrm{u}, \mathrm{v}) = \begin{bmatrix} f_1(\mathrm{x}, \dot{\mathrm{x}}, \mathrm{z}, \mathrm{u}, \mathrm{v}) \\ f_2(\mathrm{x}, \dot{\mathrm{x}}, \mathrm{z}, \mathrm{u}, \mathrm{v}) \\ .. \\ f_{24}(\mathrm{x}, \dot{\mathrm{x}}, \mathrm{z}, \mathrm{u}, \mathrm{v}) \end{bmatrix} = 0 \qquad (1)$$

where $\mathcal{F}$ is a set of implicit differential and algebraic functionals f_i for $i \in \{1, 2, .., 24\}$.

The first two constraints f_1 and f_2 are due to the fact that in standalone dc microgrids the sum of the generated, stored, and consumed powers is always zero:

$$f_1 = V_{dc}\left(I_{pvdc} + I_{wtdc} + I_{batdc} - I_{load}\right), \qquad (2a)$$

$$f_2 = V_{dc} - I_{load} R_L. \qquad (2b)$$

A. Wind Branch:
Performance of the wind turbines is measured a the power coefficient curve with respect to the tip speed ratio and pitch angle [23]. Equation (3) shows the power coefficient curve of three-blade wind turbines [24]:

$$f_3 = C_{p,norm} - \frac{1}{C_{p,\max}} \times$$
$$(C_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4)\exp(-\frac{C_5}{\lambda_i}) + C_6\lambda), \qquad (3a)$$

$$f_4 = \lambda - \frac{Rad \times \omega_r}{U_x}, \qquad (3b)$$

$$f_5 = \lambda_i - (\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1})^{-1}, \qquad (3c)$$

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where λ and β, respectively, are the tip speed ratio and pitch angle. Rad is the radius of the blades and $C_{p,\max}$ is the maximum achievable power coefficient at the optimum tip speed ratio of λ_{opt} [24]. The experimental coefficients $C_1 - C_6$ are defined in Table II and λ_i is an intermediate variable.

Equation (4) presents the connected PMSG generator:

$$f_6 = \frac{d\omega_r}{dt}(t) - \frac{1}{J}(T_e - T_m - F\omega_r), \quad (4a)$$

$$f_7 = -T_e \times \omega_r - I_{wtdc} \times V_{dc}, \quad (4b)$$

$$f_8 = -T_m \times \omega_r - (C_{p,norm}(\frac{U_x}{U_{x,base}})^3 P_{nom}. \quad (4c)$$

Energy management strategies of microgrids must estimate the dc bus voltage level deviation from its set point in about every 5–10 s [13]. It means that except the angular velocity ofthe generator (4a) all other fast voltage and current dynamics can be ignored. It is also assumed that there is no mechanical and electrical losses through the powertrain and therefore theelectromagnetic power given by (4b) is equal to the output electricalpower of the wind branch. Equation (4c) shows that the PMSG is connected directly to turbine, which rotates at low speed, and therefore needs to havemultiple pole pairs [22]. Hence, the electrical frequency is times faster than the mechanical angular velocity . The shaftinertia and the combined viscous friction coefficientof PMSG .where , , and are, respectively, the voltage,current, and state of charge of the battery bank. is the filtered value of the battery current with the time constant of and is the actual battery capacity. The experimental parameter requires being identified for each type of battery while the maximum amount of the battery capacity, , internal resistorof battery, , and the battery constant voltage, , aregiven by manufacturers (see Table II).By ignoring the discharging mode of the battery bank operation, the bi-directional converter acts as a boost-type converter [(8d)–(8e)].

C. SOLAR BRANCH

The equivalent electrical circuit of the PV module [27], [28] mis used to mathematically model the solar branch, consisting of a PV array and a boost converter [29]. Eq. (9) shows thecharacteristic equations of a PV array, consisting ofPV modules: power, either from the generator's stator Qs controlled by the RSC or from the GSC Qg [10]. Since the inductance difference for the secondary and tertiary winding of the three-winding transformer affects the amount of reactive power transmitted to the power grid, the three winding ratio is assumed as 1:1:1 for simplicity. The control of the back-to-back power converter is described in [11]. As recommended in IEEE 519-1992, harmonics higher than 35th should be explicitly limited [12]. If a simple L filter is assumed to be used, the current ripple amplitude is jointly decided by the dc-link voltage, the switching frequency, and inductance value [13]. For a typical 2-MW DFIG-based wind turbine system, the main parameters of which are is, the lower switching current ripple will be. As aforementioned, if the reactive power is required from the grid, the value of the filter inductance also affects the modulation index. Fig. 2(b) indicates the relationship between the dc-link voltage and the reactive power of the GSC Qg (the fully modulation index is assumed). In order to fulfill the reactive power range stated in E.ON Netz [7], the DFIG system should cover up to 0.4 p.u. OE and 0.3 p.u. underexcited (UE) reactive power in respect to the generator power rating. As the p.u. value is normally defined by the power rating of the induction generator, the used p.u. value in Fig. 2(b) becomes 2.0 p.u. OE and 1.5 p.u. UE reactive power in respect to the GSC, which is five times higher than the p.u. value seen from the induction generator due to the rated slip power through the GSCA. Design Procedure of an LCL Filter As shown in Fig. 3, Lc is the converter-side inductance, Lf is the grid-side inductance, and Cf is the capacitor bank, which is connected to a damping resistance Rd . The converter current and the grid current are represented by i and ig . Moreover, the voltage of the converter output and the point of common coupling are represented by vi and vg , respectively. A step-by-step design procedure for the LCL filter is described in [3]. This design is focused on that the total inductance of the LCL filter is able to reduce to half compared to the L filter. Afterward, a proper inductance sharing into Lc (0.025 p.u.) and Lg (0.025 p.u.) is realized in order to achieve the desired current ripple reduction. The capacitance value (0.1 p.u.) is then determined by the absorbed reactive power at the rated conditions, in which the resonant frequency becomes 1.35 kHz (67.5% of fsw). The passive damping is inevitably designed to overcome the resonant problem, where its power dissipation is also taken into account [3], [13]–[15]. The used filter parameters are summarized in Table II. B. Characteristic Comparison Between L and LCL Filters If the transfer function of the PI current controller, the modulation unit, as well as some delays introduced by the digital control are considered, the open-loop Bode plots of the L and the LCL filter from the GSC current reference to the line current are then shown in Fig. 4. It is clear that the magnitude and phase characteristic between the L and LCL filters are exactly the same at lower frequency, if the PI parameter used in the current controller is under proper design. It is also noted that the smaller magnitude of the LCL filter appears at the switching frequency compared to the L filter. Moreover, the damping of the LCL filter has a better performance compared to the L filter above the switching frequency

CONCLUSION

This paper has studied the influence of the grid filter inductance on the current ripple and the reactive power range for a DFIG wind turbine system. Then, an optimized LCL filter design is achieved with half value of the total inductance compared to the pure L filter. Due to the existence of the two possibilities to generate the demanded reactive power for the

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DFIG system—controlled by the RSC or controlled by the GSC—each of them is analyzed in terms of the DFIG loss and the power converters loss. It is concluded that although the compensation from the GSC significantly increases the power loss of the GSC itself, it will still have lower total loss dissipation of the whole DFIG system, as the compensation approach by the RSC will impose the DFIG loss as well as the RSC loss. Based on a typical annual wind speed distribution, the loss of energy per year is finally discussed. It can be seen that the injection of reactive power is actually not free of charge. Assuming that the cost the offshore wind power is 0.2 Euro/kWh, compared with the NOR of 1.60% annual energy loss (32.2k Euro), if the OE reactive power is injected by the RSC, it will increase to 2.05% annual energy loss (41.3k Euro) when the reactive power is needed all year around. On the other hand, if the grid filter is properly designed and the OE reactive power is supported by the GSC, the annual energy loss becomes 1.98% (39.7k Euro), which implies 3.41% (1.6k Euro) energy saving per year compared to the OE reactive injected by

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