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Energy Management Method for Doubly Fed Induction Generator with Energy Storage

***Abstract**. The paper describes metod of energy management in standalone doubly fed induction machine supported by supercapacitor energy storage coupled to the DC link of main back-to-back converter through additional bidirectional DC/DC converter. The main finding presented in the paper are the rules according to which the management of energy in this system is feasible. The implementation of this management presented in the paper, based on PI controllers, is only one way, but the rules that govern the behavior of the system may be adapted to other ways eg. based on fuzzy control.*

Streszczenie.** W artykule opisany jest sposób zarządzania rozpływem energii w układzie prądnicy dwustronnie zasilanej pracującej na wyspę wspomaganej superkondensatorowym zasobnikiem energii sprzężonym z obwodem DC przekształtnika back-to-back prądnicy za pomocą dodatkowego dwukierunkowego przekształtnika DC/DC. Głównym osiągnięciem przedstawionym w artykule jest znalezienie zasad według których zarządzanie energii w tym układzie jest możliwe do zrealizowania. Realizacja tego zarządzania oparta na regulatorach PI jest tylko jednym ze sposobów, ale reguły rządzące zachowaniem układu mogą być adoptowane również do innych sposobów np. opartych o sterowanie rozmyte.* (Zarządzanie rozpływem energii w układzie prądnicy dwustronnie zasilanej z magazynem energii***)

Keywords: DFIG, doubly-fed induction generator, DPC, direct power control, unbalanced grid.
Słowa kluczowe: MDZ, maszyna dwustronnie zasilana, DPC, bezpośrednie sterowanie mocą, sieć asymetryczna.

Introduction

Doubly fed induction machine widely used in multi-megawatt grid connected variable speed wind turbines [1][2][3], can also operate as standalone power generators [4][5][6]. Nonetheless, it can operate with other types of energy sources as well [7][8][9]. The doubly fed induction generator can also be coupled with primary movers other than wind turbines, i.e. internal combustion engines ICE [10] or hydroelectric plants, where it is possible to place the energy storage close to the main power electronic converter as shown in Fig. 1.

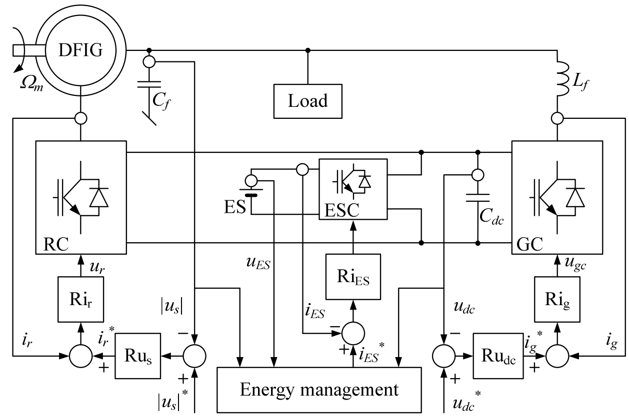

Fig. 1. Scheme of analyzed standalone DFIG with energy storage and general concept of control system.

The control methods of the rotor side converter RC responsible for stabilization of the stator voltage amplitude and frequency have been discussed in [4]-[8]. In [5], the extended sensorless control with stator voltage negative sequence and harmonics components elimination and torque pulsations reduction for DFIG feeding nonlinear and unbalanced load has been described. The reference output voltage magnitude equals the rated value. When there is energy surplus and the energy storage is fully charged, the generated voltage will be kept in this value. Stator voltage oriented current control of the grid side converter GC stabilizing the DC link voltage has been used in the standalone DFIG system and details are described in [5]. Current limits of both RC and GC converters must be set adequately, to avoid GC saturation operation in the steady state, when no energy storage is connected to the DC link or when the energy storage is fully charged or discharged.

Steady state properties of DFIG with energy storage – maximum ratings vs. speed

Connection of the energy storage unit with the DC link of back-to-back power electronic converter increases the power available instantaneously from the generation system. In case of generators like cage induction generator or synchronous generator with series converter, the power available from such a hybrid system is limited to the power of GC independently on the type of primary mover. In the doubly fed induction generator the rated power of the back-to-back converter is reduced in relation to the total power of the system. Power available from the system supported by energy storage depends strongly on the primary mover mechanical characteristic. Fig. 2 presents the characteristic of possible power available in different points of the system, for the primary mover with fixed torque in the whole range of speed (Fig. 2a), and for the primary mover with the dependence of primary mover torque as a square function of the mechanical speed (Fig. 2b).

The rotor power P_r equals

(1) $$P_r = -sP_s$$

where *s* is a slip, and P_s is a stator generated active power.

Neglecting power losses in the machine and power converter, mechanical power P_m equals

(2) $$P_m = P_s + P_r = P_s(1-s)$$

so

(3) $$P_s = \frac{P_m}{(1-s)}$$

and

(4) $$P_r = \frac{s}{(s-1)} P_m$$

The power taken from the energy storage is described by eq. (5). The total power P_t is a sum of the stator power P_s, which can be produced by DFIG and the power, which can be additionally transferred by GC. It also equals a sum of mechanical power P_m and power taken from energy storage P_{ES} (eq. (6)).

(5) $$P_{ES} = P_{GC} - P_r$$

(6) $$P_t = P_s + P_{GC} = P_m + P_{ES}$$

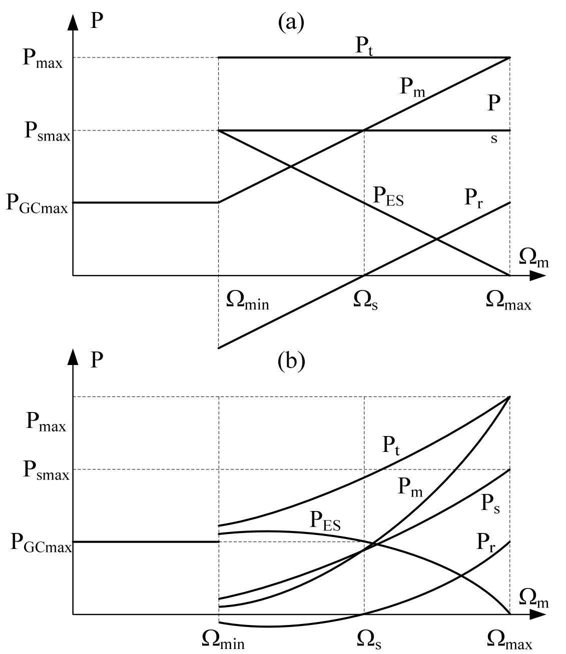

Fig. 2. Maximum power characteristics P_t of the standalone DFIG with energy storage for difference sources, a) fixed torque primary mover, b) torque as a speed square function of primary mover.

In the case of fixed torque primary mover the mechanical power P_m is proportional to the speed. The converter feds the slip power P_r to the rotor (negative sign in relation to the stator generated power) in sub-synchronous range and delivers the slip power to the load (the same sign as stator generated power) in super-synchronous range, whereas the stator power is fixed in the whole range. In sub-synchronous range the energy storage may provide the slip power P_r to the machine's rotor and the second part may be transferred by the grid GC to the load. It results, that the total power P_t of the generation system can reach the maximum value possible for the generation unit in the designed range of speed (Fig. 2a). In the case of wind turbine, the primary power P_m is a cube function of speed and the total power is smaller than maximum value in whole range except the maximum speed (Fig. 2b).

Overview of control methods for DFIG systems with energy storage

Grid connected DFIG systems with energy storage

The energy storage integration with a doubly fed induction generator has been discussed in the papers mainly at the angle of improved grid integration of a wind driven grid connected doubly fed induction machines [12]-[17]. One of the first papers dealing with energy storage supporting doubly fed induction machine for wind power applications is [12]. Authors proposed direct connection of the battery energy storage with DC link of back-to-back converter and the proposed method was a simple fixed active power reference despite the wind speed. It is required to change the control method in case of full charge or discharge of the energy storage, but these cases has not been described in the paper. In [13] the same Authors proposed the energy storage support for wind energy conversion system with DFIG, through the two quadrant converter between supercapacitor energy storage and DC link. Authors rightly noticed, that full charge or discharge of the energy storage requires modification of the control methods for both, GC and storage interfacing converters, but they do not discussed in detail such required modifications. The Authors did not used inner loop of the energy storage current control, what is unusual in a power electronics control strategies. In the cited paper, only a simulation results have been performed. Further publication of the same Authors [14] is related to smooth the wind-induced power variations and improvement of fault right through FRT properties of grid connected DFIG. Authors propose to use the fuzzy logic method, based on the power network voltage and energy storage voltage for creating the roles to control the total grid power and pitch angle. Method of supercapacitor energy storage integration and DC voltage control is the same like in previous [13] paper.

In [15] the grid connection operation of DFIG with DC/DC converter integrating supercapacitor with DC link has been described. The proposed method of energy management bases only on the DC link voltage regulation by the DC/DC battery converter. The method requires change of the control method in the case of full charging or discharging of the battery working as the energy storage, because the energy storage converter cannot keep longer the DC link voltage on the reference level without deep discharge or overcharge of energy storage respectively. The transient states caused by full charge or discharge of the energy storage have not been performed and discussed. Authors wrote in the introduction, that proposal of battery energy storage system application is useful not only for the energy management but also for fault right through FRT protections and can replace commonly used crowbar protections. This is a very brave statement and means that Authors are not fully familiar with the crowbar's role during FRT. Only a simulation results were presented, so the Authors could not observe real problems with rotor overvoltage during FRT, what is the main problem in such case.

In [16] the Authors proposed the system of grid connected wind turbine supported by hybrid supercapacitor-battery energy storage system. They described in details superior control of the wind turbine speed and power with pitch angle regulation and inner control methods of RC and GC of DFIG. For energy storage power management, they proposed a structure, in which the energy storage reference power is filtered by low pass filter, what gives a reference power for battery with removed quick changes. Second signal calculated as the difference between total reference power of energy storage and battery reference power is fed as reference power for supercapacitor. However, nowhere in the paper the roles of reference total power determination have been described. In this field Authors cited other papers, but the cited papers are not strictly related to this issue and to this topology of power generation system. Only simulation results have been performed.

Another paper [17] proposes a supporting action of energy storage in grid connected DFIG system, in which the supercapacitor energy storage is integrated on the AC side. From this point of view, the DFIG is an example, but in fact it doesn't matter what kind of wind generation unit will be supported, because the energy storage system control is completely independent on the control of generation unit. Authors compared the system behavior with and without supercapacitor integrated on the AC side, but some results are difficult for analysis. Enough to mention, that Authors write about system behavior in 5 seconds period after three phase short circuit, whereas the results shows the grid bus voltage increase at the instant of short circuit begin. Furthermore, the DFIG system behavior strongly depends on the control system of RC and GC converters, which has not been even mentioned in the text. One of the figures shows, that average p and q power components produced by the STATCOM converter with integrated supercapacitor are close to zero, what means that this device is used only for elimination of oscillations of power, torque and speed during transients. The oscillations may be easily avoided using typical well known methods in the case of three phase voltage sags, whereas the results presented in the paper shows significant oscillations of this variables.

It clearly shows that used control method for DFIG system provides instability in case of dynamic changes of grid voltage. It seems, that it is not a problem with lack of STATCOM – supercap system or not, but the problem is with the used control method for DFIG system. However, it seems that independently on used generation structure, for wind energy conversion systems an AC side integration of energy storage is more adequate than DC side integration, due to easier and cheaper maintenance and replacement of energy storage, as well as smaller power losses.

Standalone DFIG systems supported by energy storage

Standalone operation of doubly fed induction machine has been described much less than grid connected systems. Therefore, the energy storage cooperation with standalone DFIG can be found in only a few papers. In the power system with a standalone doubly fed induction machine, the energy management method is more complicated, than in series converter based systems. In the DFIG power system without the energy storage, the RC feds simultaneously the slip active power and part of the reactive current needed for machine magnetization and required by the load, which another part is compensated by the stator connected filtering capacitors C_f. The GC is responsible for the DC link voltage stabilization.

The paper with most similar analyzed topic [18] performs the results of standalone DFIG based wind turbine supported by the battery energy storage connected directly to the DC link. Besides well known control methods for RC and GC converters, there are proposed DC link voltage controllers, which are the battery voltage controllers. These controllers modifies the reference active power of GC in case of energy storage full charge or full discharge, as well as in the case of lack of energy storage, but system operation at this specific conditions were not presented at all. However, the paper shows very interesting simulation results of complex system.

Standalone DFIG based power system with supercapacitor integrated on the DC side and battery integrated on the AC side has been described in [19]. The method power distribution between components of hybrid energy storage are the same like in [16], that means with the use of filtration of total reference power for energy storage and use of filtered low frequency signal as the reference power for battery and the signal including fast changes as reference power for supercapacitor. The paper shows good simulation results which confirms correctness of this method, but the overall structure of power system is controversial. The control methods for other converters are very well known from the other papers. Power system is not equipped with AC side connected filtering capacitors, what is obligatory to obtain high quality generated voltage in a wide range of load power and in case of nonlinear load.

Parallel operation of DFIG, supported by energy storage and dynamic voltage restorer DVR, and wound rotor synchronous generator in the AC microgrid is described in [20]. Proposed system is very complicated and require additional power converters for DVR. It means that economical advantage of DFIG system is questionable. Indeed, this is a feature of many similar complex systems with DFIG proposed in the literature. From the scientific point of view, they are interesting, but it is easier and cheaper to use a series power systems. Very often Authors of papers presenting results in this field forget that rated power of electronic converters (rotor and grid side) are limited. Even, if in the laboratory they use oversized converters for safety reasons, the current limits has to be implemented on the proper level adjusted to the used machine power and not on the level of used power electronics devices. Similar issue is with the control methods. With the unsaturated power converters almost everything is possible, but in a real system, in which the converters are sized to 25% of the rated power of whole system, even very sophisticated control may not give expected results, because limitations are on the power circuit side, not on the control method side.

Power management in energy storage equipped standalone DFIG system

The energy management method includes three main parts (Fig. 3). The first one is an internal control loop of the energy storage current. In the control structure it is assumed that the energy storage charging current has a positive sign. The second part is responsible for energy distribution between energy storage and the main source, and is based on the stator voltage and DC link voltage measurements, which indicate energy deficit of surplus. Required current i_{ES}^{req} referees the current value adequate to obtain energy management. The third part is based on measurement of the energy storage voltage and is responsible for protection of the energy storage against its overcharge and deep discharge. Additional signal i_{ES}^{stop} causes decrease of energy storage charging or discharging current in the case of full charge or discharge of storage.

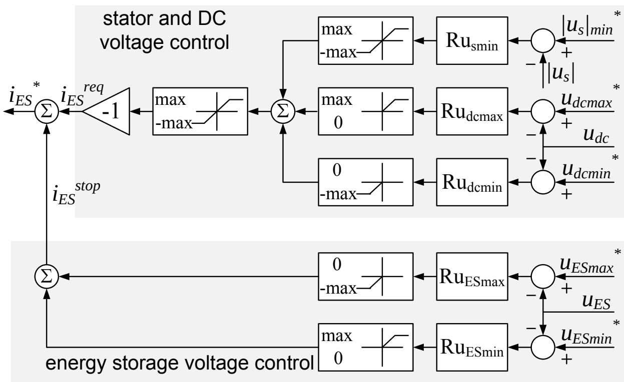

Fig. 3. Scheme of the energy management method with deep discharge and overcharge protections.

The crucial part responsible for energy distribution between the main source and the energy storage, consists of the main controller Ru_{smin} responsible for keeping the stator voltage at minimum level during the energy deficit (energy storage discharge) and during the energy surplus (energy storage charge). The stator voltage can be higher than minimum reference value $|u_s|_{min}^*$, when the energy surplus is higher than the energy, which can be consumed by the energy storage. This is possible in case of fully charged energy storage or in the case of GC saturation during the storage charge or during energy storage converter saturation during storage charge. The stator voltage may be lower than minimum reference value $|u_s|_{min}^*$, when the energy deficit is higher than the energy which can be delivered by energy storage. This is possible in case of fully discharged energy storage or in the case of GC saturation during the storage discharge or during energy storage converter saturation during storage discharge.

In case of GC saturation, the DC voltage may decrease (during ES charge) or increase (during ES discharge), and it is necessary to reduce charging or discharging current of the energy storage converter respectively, depending on the DC link voltage error sign, to limit the amount of energy taken or delivered by energy storage. Thus, two additional controllers Ru_{dcmin} and Ru_{dcmax} are introduced to keep the DC voltage between minimum u_{dcmin}^* and maximum u_{dcmax}^* value. These two controllers Ru_{dcmin} and Ru_{dcmax} can be treated as one controller with a dead zone between u_{dcmin}^* and u_{dcmax}^*. Such a structure allows to obtain protection against the DC link voltage either dip or swell during GC saturation. Saturation levels of each controller are selected to obtain the storage current in range from minimum (negative sign) to maximum (positive sign) respectively.

Independently on the energy surplus or deficit, it is necessary to consider the energy storage state of charge to protect the energy storage against deep discharge and overcharge. The positive charging current is brought to zero by Ru_{ESmax}, to stop charge, when the energy storage voltage reaches maximum admissible level, whereas the negative discharging current is brought to zero by Ru_{ESmin}, to stop discharge, when the energy storage voltage reaches minimum reference value. When the energy storage is off, the system operates as the one not equipped with the storage. In this case, the DC link is maintained on the u_{dc}^* level controlled by the GC. In case of energy surplus, the stator voltage is stabilized at $|u_s|^*$ level by rotor side converter, whereas during energy deficit the stator voltage is lower than the minimum value $|u_s|_{min}^*$, until there is enough energy in the system for stable operation. For significant deficit of energy, the GC may operate in saturation. Then, the DC link voltage drops below the minimum level and the system collapses. All possible states of stable operation are as shown in the Table 1. The case of GC current saturation and no energy storage or fully discharged energy storage is unstable and cause the stator voltage black out.

Possible states of DFIG supported by energy storage

Standalone operation of DFIG without energy storage has been deeply described in [5], and the same sensorless method was implemented to obtain results for this paper. The method of compensation of generated voltage asymmetry and harmonics during nonlinear and unbalanced load supply was described and laboratory tests results in steady and transient states has been shown, therefore this issues will not be described here. The state described [5] is equivalent to the state with storage equipped standalone DFIG with rotor converter operating under limit, that means with power surplus higher than energy storage can take.

Naturally it is possible stable operation with stator voltage drop during overload of no storage equipped standalone DFIG unit, in which the rotor converter operates with current saturation. The necessary condition for this stable operation is no current saturation of grid side converter GC. This converter has to be able to provide required amount of active power to the DC link to stabilize the DC link voltage necessary for stable operation. Current saturation of GC converter in case of no energy storage (equivalent to fully discharged energy storage) implicated the stator voltage black out due to energy deficit in DC link.

The possible states of standalone DFIG with energy storage coupled in DC link are shown in the Table 1.

Table 1. Possible states of stable operation of standalone DFIG system with energy storage

Case no.	GC current limit	value of $|u_s|$	value of u_{dc}
1. operation with energy surplus (GC unsaturated)	-	$|u_s|_{min}^*$	u_{dc}^*
2. operation with energy surplus (GC saturated)	+	$\geq|u_s|_{min}^*$ $\leq|u_s|^*$	u_{dcmin}^*
3. operation with overload (GC unsaturated)	-	$|u_s|_{min}^*$	u_{dc}^*
4. operation with overload (GC saturated)	+	$\leq|u_s|_{min}^*$	$\underline{u}_{dcmax}^*$

The cases are strictly related to the topic of this paper and require energy management method for proper operation. In the cases 1-4, the RC is saturated, what means that rotor current reaches maximum value. Energy storage is not fully charged or discharged, thus output signals of energy storage minimum and maximum voltage controllers are equal to zero

$$out(Ru_{ES\max}) = out(Ru_{ES\min}) = 0$$

so

$$i_{ES}^{stop} = 0$$

and reference current of energy storage i_{ES}^* equals the required current value

$$i_{ES}^* = i_{ES}^{req}$$

Case 1 is related to energy surplus from primary mover. For this case the energy management controllers states are as follows:

$$out(Ru_{s\min}) \in (-\max, 0)$$
$$out(Ru_{dc\max}) = \max$$
$$out(Ru_{dc\min}) = -\max$$

Thus, the current i_{ES}^{req} required for energy management, which is the sum of all these controllers output signals, is in the range from zero to maximum and depends only on the state of stator minimum voltage controller Ru_{smin}.

$$i_{ES}^{ref} = -out(Ru_{s\min}) \in (0, \max)$$

Case 2 is also related to energy surplus, but with GC saturation. The energy management controllers states are:

$$out(Ru_{s\min}) = -\max$$
$$out(Ru_{dc\max}) = \max$$
$$out(Ru_{dc\min}) \in (-\max, 0)$$

Thus, the current i_{ES}^{req} required for energy management is in the range from zero to maximum value and depends only on the state of DC minimum voltage controller Ru_{dcmin}.

$$i_{ES}^{ref} = -out(Ru_{dc\min}) \in (0, \max)$$

Case 3 is related to overload, and deficit of energy from primary mover is fully compensated by energy storage unlimited by GC. For this case, the GC takes the missing energy from DC link and keeps the stator voltage at minimum level. The management controllers states are:

$$out(Ru_{s\min}) = \in (0, \max)$$
$$out(Ru_{dc\max}) = \max$$
$$out(Ru_{dc\min}) = -\max$$

Required current i_{ES}^{req} is in the range from minimum value to zero and depends only on the state of stator minimum voltage controller Ru_{smin}.

$$i_{ES}^{ref} = -out(Ru_{s\min}) \in (-\max, 0)$$

Case 4 is also related to overload, but with saturated GC, and the energy taken from storage is limited by GC saturation. The stator voltage drop cannot be fully compensated by energy from energy storage due to the GC saturation. The energy management controllers states are:

$$out(Ru_{s\min}) = \max$$
$$out(Ru_{dc\max}) \in (0, \max)$$
$$out(Ru_{dc\min}) = -\max$$

Required current i_{ES}^{req} is in the range from minimum value to zero and depends only on the state of DC minimum voltage controller Ru_{dcmin}.

$$i_{ES}^{ref} = -out\left(Ru_{s\,\min}\right) \in \left(-\max, 0\right)$$

Results of the laboratory tests with small power unit

The laboratory tests have been made with a small power 2.2kW doubly fed induction machine. Scheme of the laboratory unit is presented in Fig. 4. As the used machine has much lower rotor voltage than the stator voltage, a matching transformer is used between stator and GC. Thus, the RC and GC converters may have the same current and voltage rated parameters, like it is in a real DFIG systems. The used L_f inductance 2.5mH is higher than leakage inductance of matching transformer 0.2mH (referred to the GC converter side), so the transformer can be treated as the ideal one. The driving machine is an externally excited DC motor with maximum power equal to 5kW at 1.5krpm, so it is large enough to drive tested DFIG system.

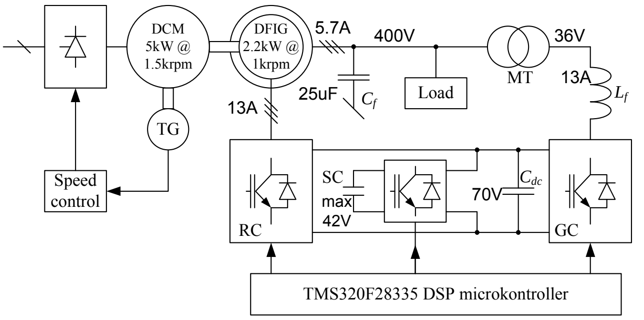

Fig. 4. Scheme of the laboratory test bench used for verification of the power management method in the standalone DFIG based power generation system with supercapacitor energy storage.

Parameters of the machine and current limitations of power converters are presented in the Table 1. The secondary side voltage of matching transformer equals 36V, what equals 33% of the rotor voltage. The reference value of the DC link voltage is set on 70V, what allows to extend the speed range more than +/- 33% around ω_s.

Table 1. Parameters of the electric machine and laboratory unit

SYMBOL	PARAMETER	VALUE
P_N	Rated power	2.2kW
u_{sN}	Stator rated voltage	400V
u_{rN}	Rotor rated voltage	108V
i_{sN}	Stator rated current	5.7A
i_{rN}	Rotor rated current	13A
i_{gN}	Grid converter rated current	13A
u_{MTs}	Transformer sec. voltage	36V
C_f	Stator capacitance	25uF
u_{SCmax}	Supercpacitor max. voltage	42V
C_{SC}	Capacity of energy storage	67F
	Sampling/switching frequency	2kHz

The possible states of the DFIG based power system with the energy storage are presented in Figures 5 and 6 with oscillograms of the voltage and current signals, which are the most important for the energy management. Figure 5a presents the sequence from initial state, in which the storage is fully charged and there is energy surplus in the power system. Next state shows the maximum energy storage discharging current, but in the range of the energy deficit almost fully compensated by the energy storage, that means with the stator voltage slight drop below the minimum level (case 3). Third state is a GC limitation, in which the stator voltage is kept also a little bit below the minimum level, and the DC link voltage controlled at the maximum value (case 4). Fourth state is the energy storage charging with the GC current saturation (case 2).

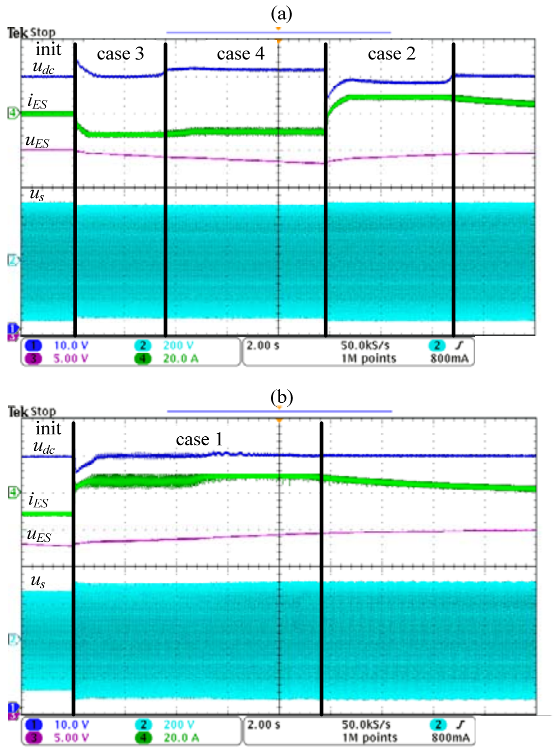

Fig. 5. Oscillograms presenting the voltage and current signals during different states – charging during energy surplus, and discharging during energy deficit.

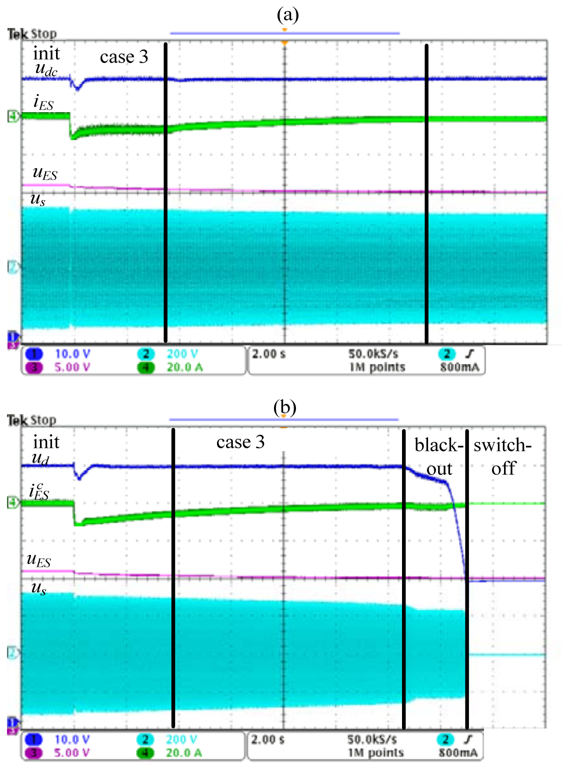

Fig. 6. Oscillograms presenting the voltage and current signals during full discharge of storage – continuous operation with the stator voltage amplitude

It means the energy surplus is higher than the one, which can be delivered by the GC to the DC link and further to the energy storage. The RC leaves the saturation region and the stator voltage is controlled at nominal level u_s^*.

The last state in this Figure is full charge of the energy storage, when the storage current is successively decreased to zero.

Figure 5b presents the process starting from initial deficit of energy with simultaneous energy storage current saturation (case 4), but with higher load than corresponding second state (case 3) in Figure 5a. Higher load means overload of the generation system and the stator voltage drops below minimum level. The second state in this Figure is the energy storage charging, initially with the energy storage charging current below maximum value and with rotor current saturation, and next with the energy storage current saturation and unsaturated RC. This transient is caused by the speed increase, what cause increase of the energy surplus higher than the one, which can be consumed by the energy storage converter. It cause the stator voltage reaches nominal value. The last state in this Figure is full charging of energy storage analogous to the last state from Figure 5a.

Figure 6a presents, after the initial state, the case of energy deficit and storage discharge. The stator voltage drops to the minimum level, and after some time the energy storage achieves minimum assumed state of charge, so its negative discharging current increases to zero. However, the energy deficit was not significant, so the system operates stable but with the stator voltage below minimum value. The analogous case of minimum assumed state of storage charge is presented in Figure 6b. The difference is that, the test has been made at lower mechanical speed, so less energy was available from the main source. After full discharge of the energy storage, the DC link voltage dropped to the level of energy storage voltage and the system was switched off to do not further discharge the energy storage by uncontrolled current.

Conclusions

The maximum possible power of the load supplied from isolated power systems depends on the speed range and to increase the power at low speed, the energy storage can be used. The standalone doubly fed induction generator can stably operate during overload, but the stator voltage drops below the rated value. Adding the energy storage to the DC side of main back to back converter improves the voltage quality, but it has to be taken into consideration, that in case of wind turbine as the primary mover it is not possible to obtain full power at the speed lower than maximum.

In order to obtain stable operation a dedicated energy management method is necessary, and this method has several functions. Its main function is the stabilization of the AC stator voltage at not lower than the minimum level, and this voltage is the indicator of energy deficit or surplus. At the same time, the method avoids uncontrolled change of the DC link voltage over the limited levels. Additionally, there are implemented protections against the energy storage deep discharge and its overcharge.

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under limit (a), and unstable with the stator voltage collapse (b).

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