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Double Side Control of Wound Rotor Induction Machine for Wind Energy Application Employing Half Controlled Converters

D. Panda, T. A. Lipo*

Rockwell Automation Advanced Technology Lab, Richmond Heights, Ohio 44143, USA, dpanda@ieee.org

*Department of Electrical and Computer Engineering University of Wisconsin, Madison, WI 53706, USA, lipo@engr.wisc.edu

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

Double side control of wound rotor induction machine for wind energy application employing half controlled converters

Debiprasad Panda [1], Thomas .A.Lipo [2]
[1] Rockwell Automation Advanced Technology Lab,
Richmond Heights, Ohio 44143, USA, dpanda@ieee.org
[2] Department of Electrical and Computer Engineering
University of Wisconsin, Madison, WI 53706, USA, lipo@engr.wisc.edu

Abstract – **A double side converter fed wound rotor induction machine control for a wind energy application is proposed in this paper. In order to reduce the cost of a wind generator system, a new configuration using half controlled converters for both the stator and rotor circuit as well as for the line side is proposed. The proposed controller reduces the required KVA rating of both machine side and line side converters, improves the efficiency of the wind generator, helps operating over a wide speed range and supports near unity power factor interface with the grid. It is shown that the combined KVA rating of both the machine side converters are even less than that of the machine side converter for a conventional rotor side control configuration. Also, both stator and rotor side being connected to the grid through two power stages, the system will be least affected by the fault or disturbances in the gird. The proposed configuration is simulated for a 30kW wound rotor machine in SABER and the simulation results are presented.**

Keywords: wound rotor induction machine, wind generator, Super-synchronous generating mode, half controlled converter, reduced switch configuration.

List of symbols:

V_s *: stator terminal voltage*

V_r *: rotor terminal voltage*

$i_s = i_{sd} + ji_{sq}$ *: stator current*

$i_r = i_{rd} + ji_{rq}$ *: rotor current*

i_{ms} *: stator flux magnetizing current*

ψ_s *: stator flux*

ψ_r *: rotor flux*

ψ_m *: air gap flux*

T_q *: electromagnetic torque*

L_0 *: magnetizing inductance*

σ_s *: stator leakage factor*

σ_r *: rotor leakage factor*

e_s *: stator induced voltage*

e_r *: rotor induced voltage*

ω_s *: stator angular frequency*

i_s^r *:stator current in rotor reference frame*

i_r^s *:rotor current in stator reference frame*

μ *:angular position of stator magnetzing flux*

ε *:angular position of the shaft*

I. INTRODUCTION

The state-of-the-art technology for wind power employs a doubly-fed machine with only rotor side control where the stator is directly connected to the grid [1-4]; which leads to significant reduction in cost. However, such systems operate only over a limited speed range; typically field weakening is not possible and circulating power flows between the stator and rotor circuit in sub-synchronous generating mode. Also, the stator of these systems being directly connected to the grid, suffers from the disturbances and faults occurring in the grid. By employing power converters both in the stator and the rotor side, some of these problems can be eliminated. In addition, the excitation current can be shared amicably between the stator and the rotor of the machine. By doing so, the winding design (copper volume) and losses in the machine as well as in the power converter can be optimized and the machine size may be reduced. A control algorithm employing expensive full bridge converters for both the stator and the rotor was reported in [5, 6] for high power motoring application. In a recent publication [7] by the present authors, less expensive half controlled converters are proposed for machine side control; but, in line side still an expensive full bridge converter was used. In this paper, less expensive half controlled converters are proposed for both the machine and line side control without any major sacrifice in the performance of a wind generator.

In the organization of this paper, first the operating principle of a doubly fed induction motor is explained, the different operating modes for this machine are given and the best operating regime for wind generator is chosen. Then a cost effective power converter is proposed for this operating regime; and the advantages and disadvantages of the proposed converter are discussed. After that a control algorithm for the proposed wind generation system is formulated. The algorithm is validated through SABER simulation results and finally conclusions are made.

II. OPERATING PRINCIPLE

The operating principle of a doubly-fed wound rotor induction machine is well documented in the literature [1-6]. In a doubly-fed wound rotor machine, the control can be realized either from the stator side or the rotor side or from both the sides. The machine can be controlled as a generator or a motor in both the sub- and super-synchronous operating mode. Depending on the operating modes, the power flow varies in the stator and the rotor winding of the machine and the detail power flow diagram for different operating modes are given in Fig 1.

In conventional rotor side control [1-4], with two back-to-back IGBT based power converters, all four operating modes can be realized. However, during such operation, it may be seen that in sub-synchronous generating (i) and sub-synchronous motoring (ii) modes the power flow direction through the stator and the rotor side are of opposite direction. Hence, there essentially occurs a condition where circulating power flows around the stator and the rotor and which reduces the efficiency at speeds below synchronous speed. In order to avoid such possibilities, the machine should be operated only in the super-synchronous mode. However, in conventional rotor side control scheme, the super-synchronous speed mode is achieved only above the rated synchronous speed and thus the operating speed range becomes limited.

The proposed method in this paper explores a new control scheme where the machine can be theoretically operated at any speed (speed is limited only due to mechanical restrictions) and at the same time it will operate always in super-synchronous mode. Hence, all the analysis and control of the machine for this paper will be restricted to super-synchronous generating mode (mode (iii) in Fig. 1).

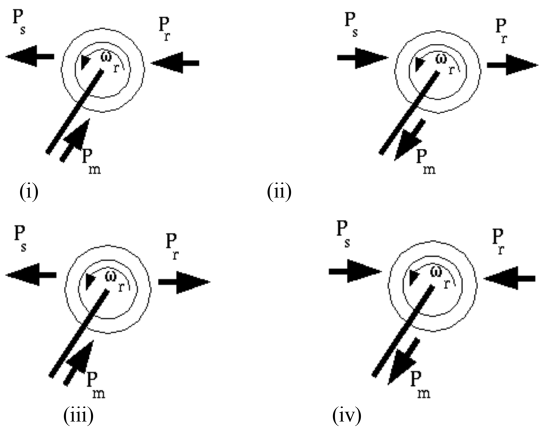

Fig. 1 Power flow diagram of a doubly-fed wound rotor induction machine for: (i) sub-synchronous generating mode, (ii) sub-synchronous motoring mode, (iii) super-synchronous generating mode and (iv) super-synchronous motoring mode

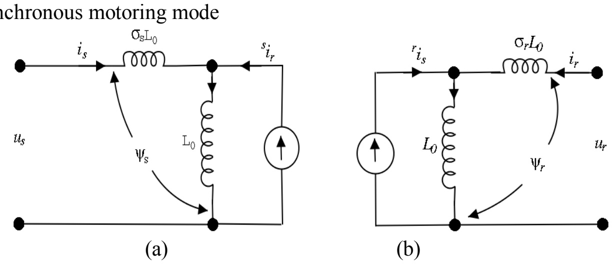

Fig. 2 Equivalent circuit diagrams of a doubly-fed wound rotor induction machine: (a) for rotor side control (LHS) and (b) for stator side control (RHS)

A. SUPER-SYNCHRONOUS GENERATING MODE

Simplified equivalent circuits of a doubly-fed wound rotor induction machine controlled from the rotor side and the stator side are given in Figs 2a and 2b respectively. In Fig. 2a, it is assumed that the rotor currents can be injected at any desired phase, frequency and magnitude. Therefore, the rotor circuit can be represented by a controllable current source. The equivalent circuit is drawn in the stator reference frame; hence the rotor current is represented as i_r^s. Similarly, when the control is exerted from the stator side the equivalent circuit can be drawn as in Fig. 2b. In the latter, the stator circuit is represented as a controllable current source. The steady-state phasor diagram for the super-synchronous generating

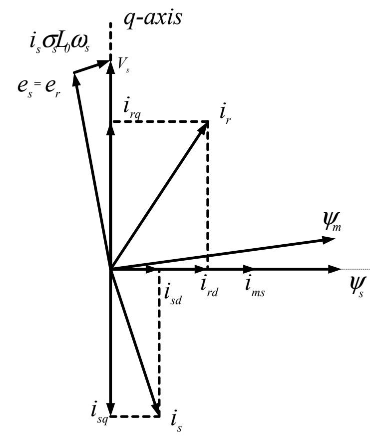

Fig. 3 Steady-state phasor diagram (stator reference frame) of a doubly-fed wound rotor induction machine for the super-synchronous generating mode

mode in stator reference frame is given in Fig. 3. In the diagram, counterclockwise direction of rotation is assumed as the positive direction. Neglecting the stator resistance, it may be assumed that the stator flux ψ_s has two components; the stator leakage component and the magnetizing component (see Fig. 2a). The former is due to the stator current alone, while the latter is due to both the stator and rotor currents. An equivalent current i_{ms} can be defined in the stator reference frame, which is responsible for the stator flux. This is termed as the stator flux magnetizing current. The direction of ψ_s (which is in phase with i_{ms}) is defined as the d-axis and, the direction of the stator voltage, which is in quadrature with ψ_s, is termed as the q-axis. It is possible to resolve i_s and i_r^s along and perpendicular to i_{ms}. The components of the currents along the d-axis are represented with subscript 'd', and those along the q-axis with subscript 'q'. The mathematical relations between the currents in this stator flux reference and the expression for the torque are given below.

$$i_{sq} = -(n_r / n_s) \times i_{rq} \quad (1)$$

$$i_{ms} = (n_r / n_s) i_{rd} + i_{sd} \quad (2)$$

$$T_q = \frac{3}{2}\frac{P}{2} i_{ms} i_{rq} \frac{L_0}{1+\sigma_s} \quad (3)$$

From the above equations, it may be seen that the magnetizing current of the machine i_{ms} is a summation of the d-axis components of the stator and the rotor currents. Also, the q-axis components of both sides are simply related by their turns ratio and are of opposite direction. The same relationship can be explained with the phasor diagram in Fig. 3. The torque of the machine is a product of magnetizing component and q-component of the rotor current. Hence, torque can be controlled either by controlling flux component, the torque component or by controlling both simultaneously.

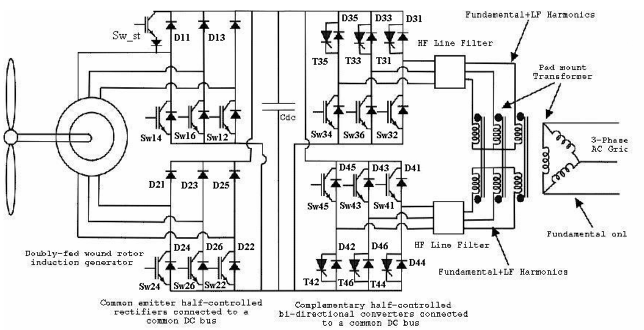

Fig. 4 Proposed wind generator system

B. PROPOSED POWER CONVERTER CONFIGURATION AND CONTROL STRATEGY

The proposed wind generator system is shown in Fig. 4. It may be seen that both the stator and the rotor side are connected to the grid through two half controlled power stages in each side. In this operating mode as mentioned earlier, the power is extracted from both the stator and the rotor of the machine and thus the converters connected to the machine windings will always function as rectifiers and the total power of the machine can be shared arbitrarily between the stator and the rotor of the machine.

Similarly, two new half controlled converters are employed for the line side. Each half controlled converter employs only three active switches and each switch is rated only for half the rated power of the wind generator. Thus, combining both the line side half controlled converters, total six active switches are used and all are rated for only half the rated power. In addition, twelve diodes and six thyristors are also used in the line side and all the thyristors and diodes are rated for only half the rated power. All six thyristors, and six out of twelve diodes (the diodes antiparallel to the active switches) are line commutated type, which are much less expensive. Thus, the line side converter employing two half controlled circuits will be much more cost effective compared to a full bridge converter (in full bridge all six switches and diodes are of inverter grade and rated for full power).

In an earlier paper [8], it was shown that the distortion in the current and voltage waveforms of a half controlled converter is somewhat less for a lagging power factor (typically 15 to 30 degree lagging current) type current commands compared to that with unity power factor and leading power factor type current commands. From Fig. 3, it may be seen the stator side terminal voltage, V_s is lagging the stator induced voltage e_s so that the machine is operating as a generator. If i_{sd} is assumed to be zero, then the stator current will be exactly 180^o out of phase with the stator terminal voltage. Hence, it may be inferred that the stator current will be lagging in nature with respect to stator induced voltage e_s and the lagging angle is dependent on the leakage inductance and the stator current. If load current is varied then stator current angle with respect to the stator induced voltage will also vary proportionately. Similarly, for any positive value of i_{sd}, the phase angle between e_s and i_s will be reduced and the power factor will be approaching unity power factor. Thus beyond a certain value of i_{sd}, the current will start leading the induced voltage.

Similar operation may be explained for the rotor side, with the help of Fig. 2b and a similar phasor diagram in rotor reference frame. In order to operate both the stator and the rotor side in the lagging power factor operating mode or reduced leading power factor condition, the excitation current through the individual stator and rotor side should be much less than the torque component of the current. The best means to achieve this result is to distribute the flux equally between the stator and the rotor windings. In such case, each individual half-controlled converter will handle only 50% of the excitation current. On the other hand, both the converters will carry the rated active component of the current. Thus, each converter will carry 1 pu active component of current and 0.5 pu reactive component current. With such an arrangement power factor in each converter can be controlled to a certain extent. For smaller load or zero load, the flux may be reduced proportional to the torque demand. Thus, by controlling the field current as a function of load, the phase currents through both the stator and the rotor windings can be achieved with less distortion.

C. COMPARISON OF KVA RATING OF THE MACHINE SIDE CONVERTER BETWEEN THE PROPOSED AND CONVENTIONAL ROTOR SIDE CONFIGURATION

In this proposed doubly-fed wound rotor induction generator system, the air gap flux producing component of the currents will be distributed equally between the stator and the rotor windings. In such case, each individual half-controlled converter will handle only 50% of the excitation current. On the other hand, both the converters will carry the rated active component of the current. Thus, each converter will carry 1 pu active component of current and 0.5 pu reactive component current.

In the conventional rotor side control scheme, the converter has to supply the full excitation current as well as the active torque component of the current through the rotor winding. If one assumes both the rated magnetizing current and the torque component of currents are equal (i.e. 1 pu each) and orthogonal to each other, the total current rating of the rotor side converter as well as the current rating of the rotor winding goes up to 1.414 pu ($\sqrt{(1^2+1^2)} = 1.414$). Hence, both the rotor side converter and the rotor windings need to be over designed by 41.4% to accommodate the magnetizing current. However, by splitting up the excitation current equally (0.5 pu) between the stator and the rotor windings, the KVA rating of each side power converter will be reduced to only 1.118 pu ($\sqrt{(1^2+0.5^2)}$ $=1.118$) of the rated power. Since each half controlled circuit is having only 3 switches instead of 6 switches for its fully controlled counter part, the KVA rating of the active switches combining both the stator and the rotor side machine end power converter reduces to only 1.118 pu of the rated power of the machine compared to 1.414 pu for its fully controlled counterpart. Thus, with the proposed power converter configuration the KVA rating of the combined machine side power converter is reduced by 30%. Using similar arguments it may be shown that with the proposed configuration, the efficiency of the combined machine side power converter will be higher than the conventional rotor side control scheme.

Following a similar analysis as above, it may be shown that by reducing the burden on rotor winding the total copper loss of the machine is expected to improve. With proposed control scheme the total copper loss of the machine will improve by 16.67% [7]. Again, in conventional scheme the losses in the rotor windings being larger the cooling of the machine will become difficult compared to the proposed method. Most important point to note here is that by running the system always in super synchronous generating mode and by employing two separate sets of power converter in both the stator and the rotor side the flow of circulating currents between the stator and the rotor side converters is avoided.

D. STARTING METHOD

It can be seen from Fig. 4 that an extra IGBT (Sw_st) switch in series with a diode are added between the DC bus and phase A of the stator winding for providing starting excitation to the machine. With this extra switch DC excitation can be provided to the stator though phase A and either one of phase B or phase C. In this paper, phase B is chosen for that purpose. Thus, controlling Sw_st and Sw16 simultaneously, a DC current can be passed through phase A and phase B, while phase C remains open circuited. This DC excitation will generate a DC flux in the stator magnetic circuit. Since, the rotor is assumed to be rotating freely by wind thrust, the rotating phases in the rotor will pass through this DC flux and voltages will be induced in the rotor windings. At this time, power can be extracted from the rotor winding to the DC bus by actively controlling the rotor side half controlled converter. After few cycles of such operation, when sufficient current builds up through the rotor winding, Sw-st will be switched off and a regular half-controlled converter for the stator side will be activated and the control will be shifted from starting mode to normal running mode. It should be mentioned here that the extra starting switch needed for this circuit is rated for only 15-20% of the rated current. Thus, this starting switch does not add significant extra cost to the system. Another alternative starting method is proposed in [7], where the special starting switch (Sw_st) is not required; instead a three phase contactor is employed between the stator winding and the grid.

E. LINE SIDE CONVERTER WITH TWO HALF CONTROLLED CIRCUITS

In the present application, the line side converter needs to convert the power from DC to AC for which the inverter or regenerative operation of the converter is essential. None of the previously investigated half controlled converters [8, 9] have the above feature. In this paper, by having a hybrid configuration employing thyristors and IGBTs, a 3-phase half controlled power converter is realized which is capable of acting as a rectifier as well as an inverter in half controlled manner. Then by combining the two complementary half controlled configuration a similar operation of a fully controlled 4-quadrant converter is achieved (see Fig. 4).

F. COMMUTATION OF THE THYRISTORS FOR LINE SIDE CONVERTER

With the proposed line side converter each leg of individual half controlled converter consists of one IGBT, one line commutated thyristor and two anti-parallel diodes. Thyristors are enabled only during inverter (regeneration) operation. During inversion, the upper half thyristors (T31, T33, T35 in Fig. 4) conduct when the respective phase voltages are positive and currents are negative (i.e. flows from the converter to the line). Similarly, the lower half thryistors (T44, T46, T42) conduct when the respective phase voltages are negative and currents are positive.

The commutation of the lower half thyristors (T44, T46, T42) can be explained with the help of Fig. 5. The symbols t_d , t_μ and t_q in Fig. 5 represents the commutation delay time, commutation time and minimum
turn-off time respectively. Normally, the lower half thyristors (T44, T46, T42) which are connected to the negative DC bus voltage, can be made conducting one at a time even when their respective phase voltages are negative given the fact that the DC bus voltage is always higher than peak line voltage. For example in Fig. 5, when

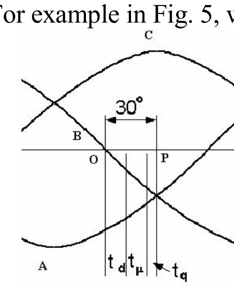

Fig. 5 Commutation methodology for the line commutated thyristors

phase A voltage is negative and phase B and Phase C voltages are positive; and also if phase A current is positive, then thyristor T44 will be conducting till either T46 or T42 are enabled. If either of them is enabled, then T44 will start commutating. In this example T44 must be commutated off between O and P. After point P, the phase A voltage becomes positive with respect to phase B and if T44 still conducts at this point, then it can not be commutated off for another cycle and similarly T46 can not be turned on. Hence, the commutation between phase A and phase B should be completed between O and P. Again, a thyristor needs to be kept off for a minimum period of t_q before the voltage across it again becomes positive. Thus, the commutation process has to be completed at least t_q (70 μs for this example) time prior to point P.

Thus, the maximum conduction period of each lower half thyristors will be from 180^0 to 330^0 while the commutation period spans from 300^0 to 330^0. The thyristors do not get turned off instantaneously. The commutation overlap time t_μ is decided by the line inductance and the current magnitude at the commence-ment of commutation. As mentioned earlier, if the commutation is delayed beyond 330^0 then commutation failure may be observed. Similarly if commutation is advanced much before 330^0, then a line side short circuit situation will arise with the incumbent phase thyristor T46 and the outgoing phase diode D44 conducting until it reaches 330^0. However, the voltage difference between the incumbent phase and outgoing phase close to 330^0 being less and at the same time two phase inductance being in series with the line voltage, the current flowing between the phases will not be significant for a small duration (about 100 micro sec). However, it will cause somewhat distortion in the current waveform since, negative current (flowing into the line) will flow through the outgoing phase when positive current is desired. Hence, it is desirable for the commutation to be completed at the close vicinity of 330^0 (not later than 330^0 and at the same time not much earlier). For a lesser current it will be wise to delay the commutation process in order to have less current distortion. Thus, a commutation delay t_d, inversely proportional to the phase current, is introduced here. Similarly, the operation of upper half thyristors can be explained for the positive half cycles.

III. CONTROL SCHEME

The proposed control scheme can be divided into machine side control and line side control.

A. MACHINE SIDE CONTROL SCHEME

A detailed machine side control block diagram is given in Fig. 6. The proposed control algorithm employs a conventional PI controller for its outer speed loop. The speed loop controller generates torque reference as its output. In order to facilitate implementation of the controller, the relation between the stator and rotor q-axis component of current, the expression of torque and expression of magnetizing currents given in Eq. (1) to Eq. (3) can be used. From the given equations, it is clear that the quadrature axis rotor current i_{rq} generates the machine torque. The stator q-axis current i_{sq} is automatically developed as the reflection of i_{rq} (see Fig.6). Thus in the control block diagram it is shown that the torque reference (T_q^*) is directly proportional to i_{rq}^*. The stator component q-axis current reference is generated in the block diagram following Eq. (1). The magnetizing current i_{ms} can be supplied from both the half controlled converters by arbitrary current sharing as given by Eq. (3). However, in the proposed method, both the converter always shares the magnetizing current equally.

In the block diagram it is shown that the total magnetizing current is multiplied with a gain of 0.5 to generate the individual magnetizing reference currents (i_{sd}^*, i_{rd}^*) for the two half controlled converters. Interestingly, the total magnetizing flux current reference i_{ms}^* is not constant for the proposed method. Thus, the iron losses using this type of controller will be reduced by the square of the magnetizing current in addition to the reduced copper loss mentioned previously. In Fig. 6 it is shown that the same as a function of the required torque T_q^* of the machine. From Eq. (3) it may be seen that the torque is a function of i_{ms} and i_{rq} so that the magnetizing current is varied as a function of load. The same is exercised in order to reduce the THD in the stator and the rotor winding currents for all load conditions.

Since, half controlled circuits drive the machine and since the excitation current capability of the same is a function of load, current is varied with load in this proposed method of excitation. Once the d-axis and q-axis current references for both the stator and the rotor windings are found, a dq to abc transformation is applied so that the three phase reference currents for stator and rotor currents are generated. A hysteresis controller is employed in each side for controlling the stator and rotor currents. The speed of the machine is sensed through a shaft sensor and by integrating this signal the position of the rotor ε is found. In the proposed control the stator and rotor windings are intended to share the power equally. In order to achieve this result, the stator and rotor frequencies are always maintained at half of the shaft frequency and their phase sequence is opposite to each other. The stator frequency sequence is maintained in the same direction as the shaft and the rotor frequency is of opposite sign. By passing the speed signal through a gain block of 0.5 and then integrating, the position of the stator flux μ is obtained. These ε and μ values are required for dq to abc transformation as shown in Fig. 6.

B. LINE SIDE CONTROL SCHEME

The proposed control block diagram for the line side converter is given in Fig. 7. In the proposed control

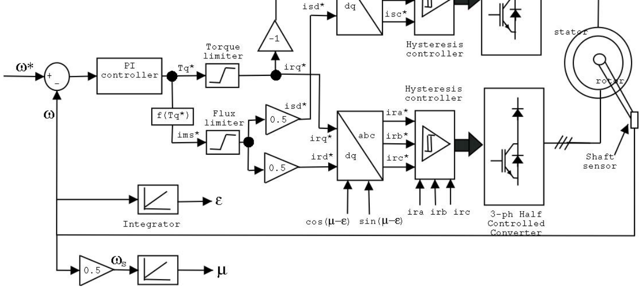

Fig. 6 Block diagram of the machine side control algorithm

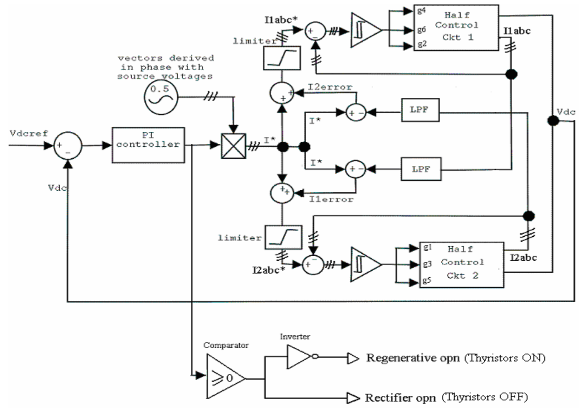

Fig. 7 Block diagram of the proposed line side control algorithm

scheme, the outer loop employs a PI controller for regulating the DC bus voltage. The output of a PI controller also determines the amplitude of current through the phases. This amplitude, when multiplied with sinusoidal unit vectors derived in phase with the phase voltage, gives the combined current references for each phase. However, the combined reference currents multiplied by 0.5 gives the reference currents for the phases of individual half control rectifiers.

In the half controlled circuits, current of each phase can follow the references only through one-half cycle when the IGBTs are in operation; whereas in the other half cycle when the thyristors are conducting the current remains unregulated and therefore can not always follow the reference. In such a case, the complementary side converter must compensate for the resulting error due to its counterpart. Hence, an active filter type control configuration has been added with the current references generated from the voltage controller. It can be seen from Fig. 7 that the individual rectifier reference currents are added to the error of the complimentary half to generate the final current references of each half controlled rectifiers. However, the current references through each phase of both the rectifiers are limited to half of the peak rated current. The current controller chosen was a conventional hysteresis current controller.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed control scheme with the half controlled power converters was investigated on a 30kW wound rotor induction machine using SABER. The simulation results with full excitation current and 25% rated load is shown in Fig. 8(i). The results at 25% load with field excitation as the function of load are shown in Fig. 8(ii). It may be seen that the current waveforms are markedly improved in case of variable field excitation. In contrast the waveforms with rated excitation and at lower load are highly distorted and the effect of the distortion is visible in the torque waveform. Hence, the proposal to vary the field excitation as function of load is validated. The steady-state simulation results at two typical operating speed (30Hz and 90Hz of shaft speed) and the FFT of the current waveforms are given in Figs 9(i) and 9(ii) respectively. It may be seen that that both the stator and rotor current waveforms are of same frequency and their magnitude differs slightly due to non-unity turns ratio between them. It is also apparent that the current waveforms are quite smooth and the corresponding FFT shows that the currents contain typical even order harmonics but their magnitude is not appreciably high.

The simulation results of starting performance with both contactor-start method [7] and the switch-start method are given in Figs 10(i) and 10(ii) respectively. In the contactor-start method (Fig. 10(i)) it may be seen that initially the stator draws the excitation current from the grid and the rotor voltages are induced due to the stator excitation. When the rotor currents build up sufficiently, the contactor is switched off and the stator side half controlled takes over the control. Similarly for switch-start method (Fig. 10(ii)), initially the DC excitation is provided through phase A and phase B and due to this excitation rotor voltage builds up and when rotor starts generating, the DC excitation is removed and the half controlled converter is switched ON with its regular control scheme. Thus, it is demonstrated that the machine can start successfully without incurring much extra cost to the system.

Similarly, the proposed line side half controlled converters were simulated with 480V line voltage and 3mH line inductances and the simulated waveforms are given in Fig. 11(i) to (iii). In Fig. 11(i), the current waveforms of individual half controlled converters (ia1, ib1, ic1 and ia2, ib2, ic2) as well as their combined waveforms (ia, ib, ic) are shown. It may be seen that individual waveforms are sinusoidal and regulated in one half cycle and unregulated nature in the other half cycle. These results are taken when the active filter algorithm was not enabled. With active filter enabled, the similar waveforms are plotted in Figs 8 (ii) and (iii) for full load and 1/3 rd load respectively. It may be seen the peak currents through individual half controlled converters (ia1 and ia2) are one-half (15A) of their combined (30A) current waveform (ia). Hence, it can be inferred that the diodes, thyristors and IGBTS of each half controlled converter is only 50% of the total power. The FFTs of the combined current waveforms are also given in the upper traces of each figure. The calculated THD at full load is found as 6.63%. At 1/3rd load, the THD is less than 3%. Also, the combined current waveform is maintained at unity displacement power factor.

V. CONCLUSION

A new double side control algorithm for a doubly fed wound rotor induction machine employing half controlled 3-phase converters is explored in this paper. Using half controlled converters the system cost is reduced and at the same time wide operating speed range and unity power factor interface with the grid is achieved. By splitting the excitation current equally between the stator and rotor windings the efficiency of the machine as well as the power converter are improved; and also it further reduces the KVA rating of the machine side converters. Even though the motoring mode of operation is sacrificed in the proposed method, for wind energy application that is not a serious problem since wind itself can be used for accelerating the machine. The machine side power converters are shoot through safe, do not require dead time delay or isolated power supply for their gate drives. Since both the stator and the rotor side frequency can be controlled at will, the zero frequency condition can be avoided so that the proposed algorithm is suitable for sensorless operation. Since, both side of the machine is connected to the grid through power converters; the system can be isolated from the grid in a controlled fashion during fault condition.

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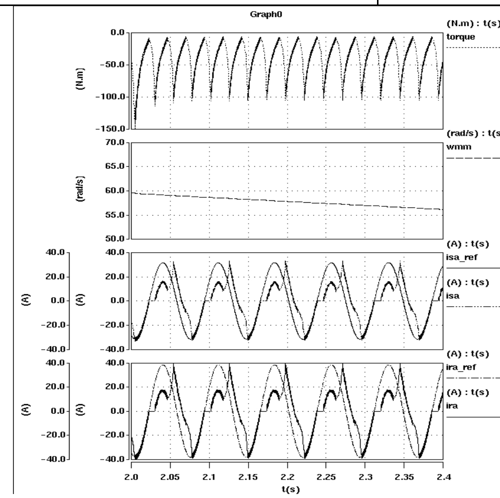
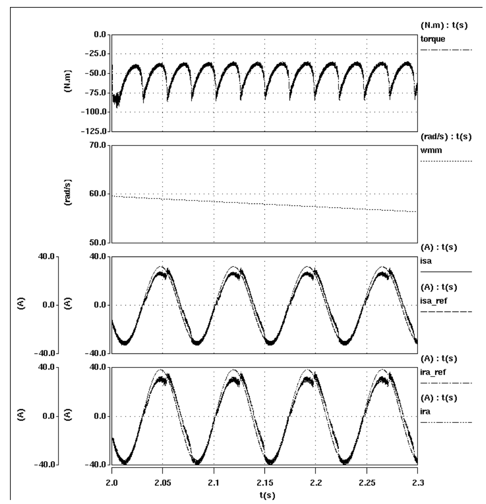
Appendix 1: Machine parameters

Power	30kW
Voltage (*Vs*)	480V
Frequency (*fs*)	60Hz
Poles (*P*)	6
Inertia (*J*)	5 kgm^2
Frictional coefficient (*B*)	0.0519247
Magnetizing inductance (Lm)	24.1mH
Stator leakage inductance ($\sigma_s L_0$)	1.326mH
Rotor leakage inductance ($\sigma_r L_0$)	1.2467mH
Stator resistance (*Rs*)	0.107 ohm
Rotor resistance (*Rr*)	0.062 ohm
Turns ratio (n_s / n_r)	1.21



(i)



(ii)

Fig. 8 Simulation results at (i) 25% load with full field excitation and (ii) at 25% load with filed excitation as a function of load

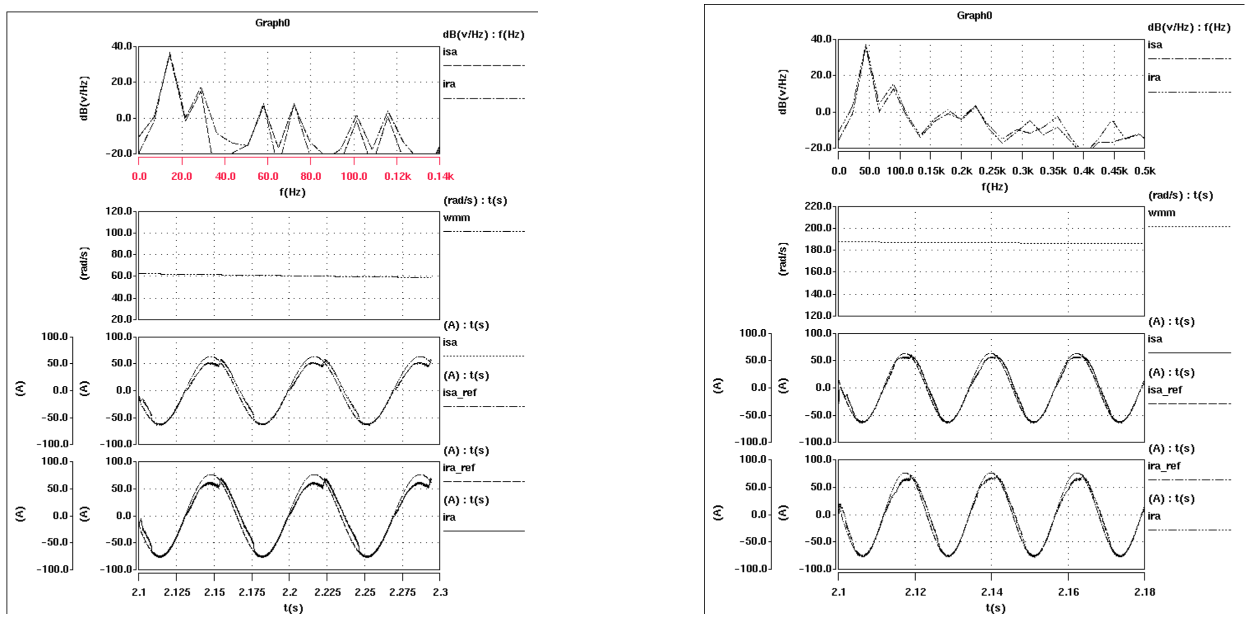


Fig. 9 Typical simulation results of a 30kW doubly-fed wound rotor induction machine: (i) with rotor shaft frequency at 30Hz (LHS) and (ii) with rotor shaft frequency at 90Hz (RHS)

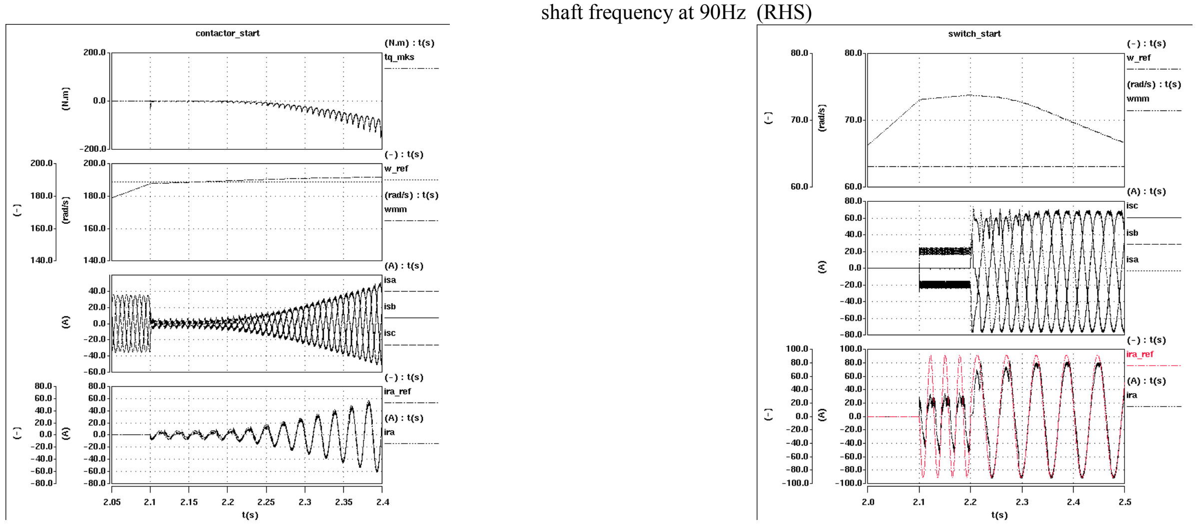


Fig. 10 Simulation results during starting of a 30kW doubly-fed wound rotor induction machine: (i) with contactor start method (LHS) and (ii) with extra switching start method (RHS)

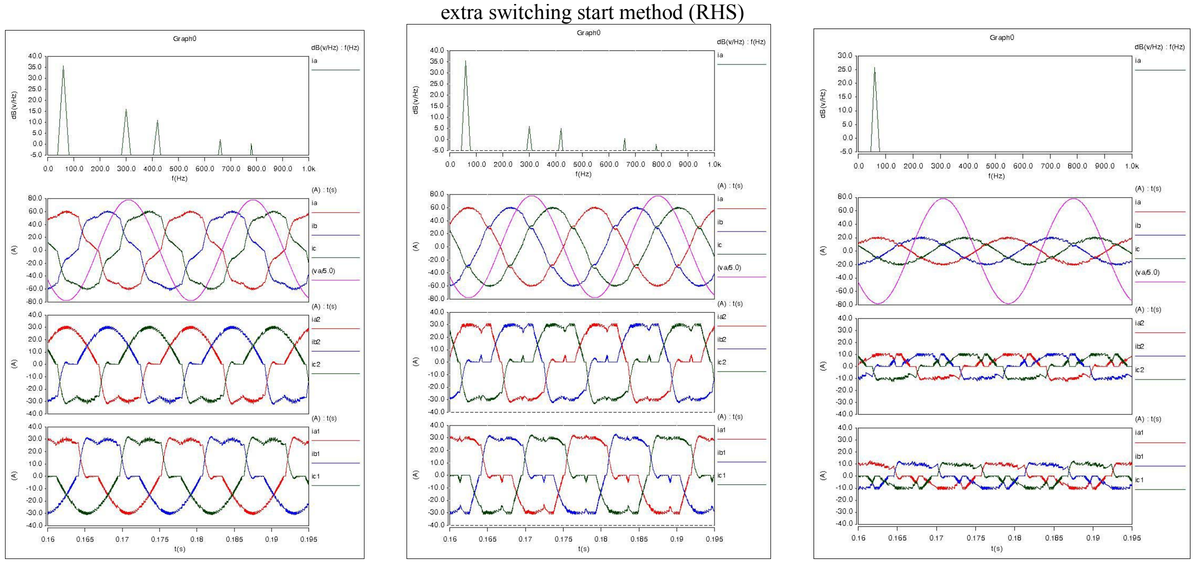


Fig. 11 Typical simulation results of a 30kW line side converter : (i) with full load and without active filter algorithm, (LEFT), (ii) with full load and with active filter algorithm (CENTER) and (ii) with 30% load and with active filter algorithm (RIGHT)