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Reduced Switch Count Double Converter Fed Wound Rotor Induction Machine Drive for Wind Energy Application

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Abstract – **A reduced switch count double side converter fed wound rotor induction machine control for a wind energy application is proposed in this paper. The outputs of two converters are combined electromechanically in the machine and are capable of sharing the power equally both from stator and rotor simultaneously. In order to reduce the cost a new configuration using two half controlled converters for both the stator and rotor circuit is proposed. The proposed controller reduces the required KVA rating of both machine side converters, improves the efficiency and helps operating over a wide speed range. 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, the proposed configuration is suitable for use with a rotary transformer since neither the stator nor the rotor winding will encounter zero frequency over the entire operating speed range. The proposed configuration is simulated for a 30kW wound rotor machine in SABER and the simulation results are presented.**

Keywords: wound rotor induction machine, half controlled converter, wide speed range operation, 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

Wind generation systems generally operate with best efficiency at variable speeds as the wind gusts dictate. Hence it is necessary to interpose a frequency converter between the variable frequency generator and a fixed frequency utility. When a squirrel cage induction machine is used, a power electronic converter equal to the KVA rating of the machine must be used since all the power transmitted to the utility passes through the converter. For high power (more than a few hundred kWs) paralleling of two or more inverters is typically an option. In the case of a wound rotor machine, the power to the utility passes through both the stator and the rotor. Hence, two independent converters can be employed in both the stator and the rotor side and the problem of paralleling can be eliminated.

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. In such a control method the power converter should be rated for the power produced by the rotor windings alone, typically 1/3 to 1/4 of the total KVA rating of the machine [1-4]. This leads to significant reduction in cost. However, such systems operate only over a limited speed range. In reality, the wind speed varies widely at different times and days of the year. Hence, a system with limited speed range capacity may not be adequate to exploit the potential of the wind fully.

By increasing the rotor side power converter the operating speed range may be extended to some extent. However, in systems where the stator is directly connected to the grid and control is exerted only from the rotor side, field weakening is typically no longer possible. Thus, topologically, the rotor side control configuration suffers from a maximum speed limitation.

By employing power converters both in the stator and the rotor side field weakening is achievable and therefore wide speed range of operation (beyond twice the rated

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speed) is possible. In addition, with this arrangement 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 can be optimized and the machine size may be reduced.

A control algorithm employing full bridge converters for both the stator and the rotor was reported in [5] for high power motoring application. However, such methods add extra cost to the system and may not be viable for wind energy application. In this paper, the major focus is to reduce the cost of the system while retaining all the advantages of a double side converter. Instead of a full bridge converter in this paper half controlled converters are employed in both the stator and the rotor side. Thus the cost of the machine side power converter can be reduced to almost half compared to the above reported method. A new control algorithm is also proposed through which the performance of the machine with half-controlled converters can be improved at all the operating range. The operating principle, control algorithm and performance of the system with the proposed configuration are presented in this paper.

II. OPERATING PRINCIPLE

The operating principle of a doubly-fed wound rotor induction machine is well documented in the literature [1-4]. In a doubly-fed wound rotor machine, the power flows through both the stator and the rotor side of the machine and the thus the control can be realized either from the stator side or the rotor side or from both the sides. Normally, four operating modes are observed in this machine. 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, 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 occur a condition where circulating power flows around the stator and the rotor and which reduces the efficiency at speeds below synchronous. In order to avoid the circulating currents between the stator and the rotor circuit, it will be advantageous if the operation of the machine is restricted to only in the super-synchronous mode. However, in conventional rotor side control scheme, the super-synchronous speed mode is achieved only when the rotor is running above the rated synchronous speed. Thus it suffers from physical speed limitation and the operation of the wind turbine gets restricted to limited speed zone. Besides, the machine can not be operated beyond twice the rated speed because field weakening is not possible when the stator is directly connected to the grid.

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 restriction) and at the same time it will operate always in super-synchronous mode. Thus the proposed control scheme promises wide speed range operation and at the same time for the whole speed range, power flows out of both the stator and the rotor windings without any penalty of circulating power flow. Since the present paper is focused on wind energy application; the machine is intended to operate always as a generator. 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).

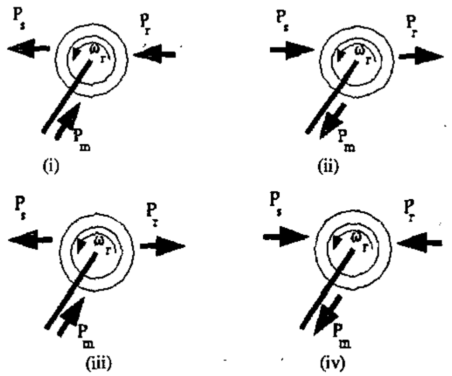
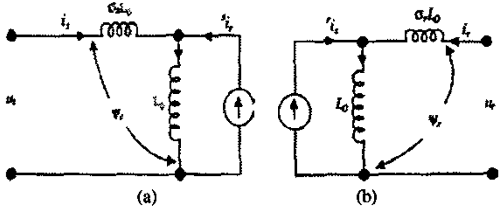


Fig. 1 Power flow diagram of a doubly-fed wound rotor induction machine for: (i) sub-synchronous generating mode, (ii) sub-synchronous motoring mode, (iii) super-synchronous generating mode and (iv) super-synchronous motoring mode



(a) (b)

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

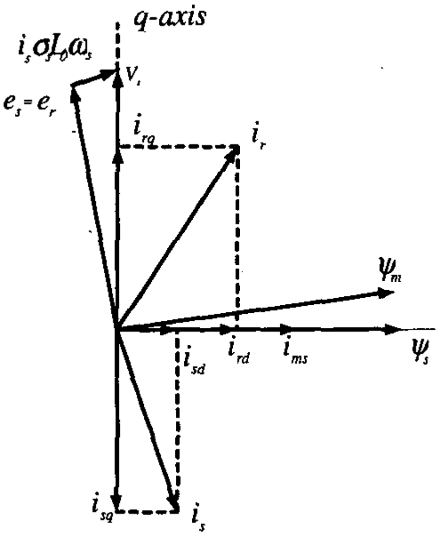


Fig. 3 Steady-state phasor diagram (stator reference frame) of a doubly-fed wound rotor induction machine for the super-synchronous generating mode

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.

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

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

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

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.

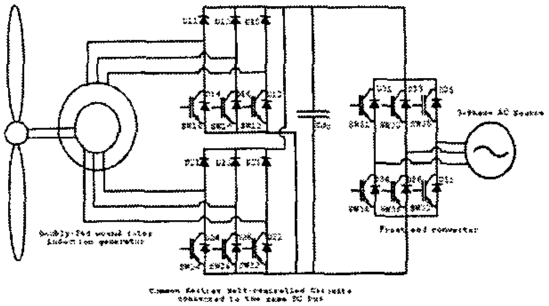


Fig. 4 Proposed configuration for double converter fed wound rotor induction machine with a common front-end converter (lower)

A. 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 power stages in each side. By employing two half controlled converters in the machine end both the stator and rotor powers are controlled. In contrast the front end of both side are connected to the utility with a single full bridge converter. Thus, the total power of the machine can be shared arbitrarily between the stator and the rotor of the machine. Since the machine is being controlled from both sides, the frequency and voltage of both sides of the machine can be varied at will. Hence, by choosing the frequencies of the stator and the rotor side that are of opposite sign and choosing their individual absolute frequencies less than the shaft frequency, the machine can be always made to operate at super-synchronous generating mode. For example, at any given frequency of the shaft, say f_{shaft}, choosing the stator frequency of the machine anything less than f_{shaft}, say f_s and by maintaining the rotor frequency as $f_r = f_s - f_{shaft}$, the machine may be made to operate in super-synchronous generating mode. In this operating mode as reported earlier, the power is extracted from both the stator and the rotor winding of the machine [3]. If the stator and the rotor frequencies are varied in the same manner as explained above, throughout the speed range the power will be generated from both the stator and the rotor and thus the converters connected to the machine windings will always function as rectifiers. Thus, the control of a doubly-fed induction generator can be realized by using two half controlled rectifiers. Since the system is connected at the front end with a fully controlled bridge converter, the unity power factor interfacing of the system is also ensured. However, a fully controlled bridge power converter at the front end handles all the power coming out of the machine which appears to be a disadvantage of this topology.

In an earlier paper, the potential of the half control circuits has been investigated [6]. It was shown that the half controlled boost rectifier circuits along with conventional control algorithm generate low order even harmonics both in the AC side current waveforms and DC bus voltage [6]. which are not acceptable for many applications. The distortion in the current and voltage waveforms can be reduced considerably if the half controlled converters are made to operate within a certain band of lagging power factor (typically 15 to 30 degree lagging current) type current commands [6]. The lagging power factor angles are function of line side inductance and the load current. However, the THD of the current waveforms become distorted with unity power factor and leading power factor type current commands. In this proposed doubly-fed wound rotor induction generator system, since both the excitation current as well as the active component of the currents will pass through both the half controlled converters and the corresponding machine windings, the machine will encounter leading current waveforms. 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 made zero, then the stator current will be 180° 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, if excitation is provided through the stator winding partially, i.e. 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.

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

By controlling the machine with two half controlled converters from both the stator and the rotor side the total KVA rating of the combined machine side converter can be reduced compared to the converter employed for only rotor side control of the machine. In the later case, 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 same (i.e. 1 pu each) and are 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. 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 the 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. At rated load since both the winding will carry 1.118 pu current and assuming the resistances of both the stator and rotor windings as R and rated active power component of the current of the machine as I_{base}, the effective copper loss of the proposed system will be $2.5I_{base}^2 R$ ($2\times 1.118^2\times I_{base}^2\times R = 2.5\times I_{base}^2\times R$). In contrast for conventional rotor side control, the rotor and the stator windings will carry unequal currents - 1.414 pu and 1.0 pu current respectively. Hence, the total copper loss of the machine for a conventional method will be $3I_{base}^2 R$ ($(1^2+1.4141^2)\times I_{base}^2\times R = 3\times I_{base}^2\times R$). Therefore, it can be concluded that in the proposed control method the total copper loss of the machine will improve by 16.67% ($\frac{(3-2.5)}{3}\times 100 = 16.67\%$). However, since half controlled circuits drive the machine from both the stator and the rotor, the current waveforms are expected to have some amount of unwanted even harmonics. The latter will introduce some extra loss in the windings as well as in the power converters. Hence the gain achieved due to the splitting of excitation currents may be offset to some extent by the losses due to unwanted harmonics in the winding currents. A detailed analysis and loss comparison between the conventional scheme and the proposed method will be taken up as a future work. Again, in conventional scheme the losses in the rotor windings are 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.

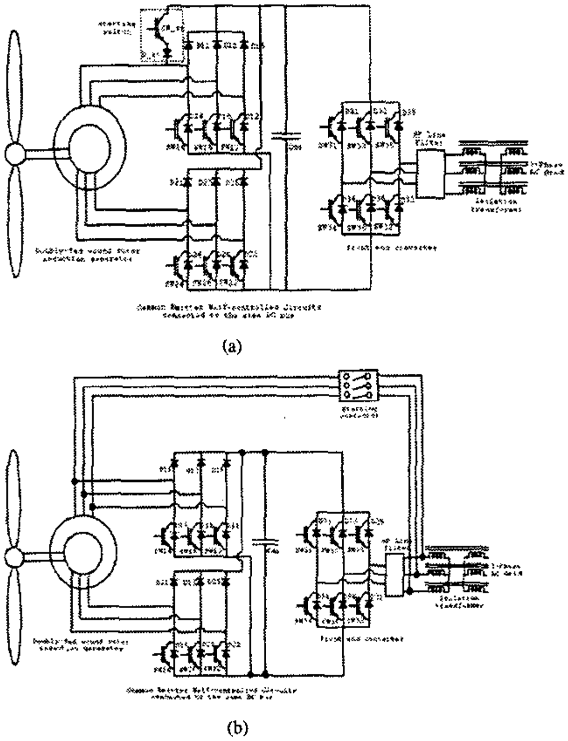
From the above discussion it may be concluded at this point that by employing double side half controlled converter the KVA rating of the machine side power converter can be improved, wide operating speed range may be achieved, possibility of temperature rise in the rotor may be reduced, possibilities of circulating currents are avoided and unity power factor interfacing through the front end converter is ensured. Besides, the half controlled power converters being much simpler, the shoot through failure is eliminated, isolated gate drive is not required and the combined switch counts being limited to six, control and PWM generation for both machine side converters can be achieved by a single DSP. Again for a given shaft speed, a combination of the stator and the rotor frequency can be chosen at will, which is clearly an advantage for operation with rotary transformer and for position estimation algorithm of the machine.

III. STARTING METHOD

As can be seen from Fig. 4 that the power flow in the half-controlled circuits are unidirectional. In this case, the power can not flow from the DC bus to the machine. Since, both the stator and the rotor windings are connected to the DC bus with similar half-controlled configurations, during starting, excitation can not be provided to the machine from either side. Hence, alternative arrangements are required. Two such alternative configurations are presented in Figs 5a and 5b respectively.

A. STARTING METHOD I (EXTRA SWITCH STARTING)

A modified circuit topology of Fig 4 is proposed in Fig. 5a, where an extra IGBT (Sw_st) switch in series with a diode (D_st) is added between the phase A of the stator winding and the DC bus. This extra switch is used 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 flows from the DC bus 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.



(a)

(b)

Fig. 5 Modified converter configuration with starting excitation capability for a double converter fed wound rotor induction machine: (a) with an extra semiconductor switch starting configuration and (b) with a contactor starting configuration

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. The above starting algorithm is verified through SABER simulation and the simulation result for the same case is presented in the subsequent sections of this paper. It is verified through simulation that the extra starting switch need not be of full rated current of the machine. A current rating of 15-20% of the rated current for the starting switch will be enough to achieve successful starting of the machine. Thus, it may be inferred that adding an extra switch for starting purpose does not add much extra cost to the system. However, after adding the starting switch the shoot-through safe operation in phase A of the stator side half controlled converter will be lost.

B. STARTING METHOD II (CONTACTOR STARTING)

Another alternative starting method is proposed in this section where the special starting switch (Sw_st) and D_st are not required, instead a three phase contactor (Fig. 5b) can be employed between the stator winding and the grid. Initially, the stator of the machine will be connected to the grid through the contactor and the complete excitation current will be provided to the machine from the stator side. When sufficient voltage buildd up in the rotor windings, the contactor will be switched off and the stator winding will be controlled by the half-controlled converter connected to the stator side of the machine and the control will be shifted to its regular running mode. In such starting method an extra contactor will be required. This method is also verified through SABER simulations. The advantage of the contactor starting method is that the shoot through safe operation of the half-controlled circuit is retained.

III. CONTROL SCHEME

A detailed control block diagram of the proposed configuration 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 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 referred. 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.3). 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.

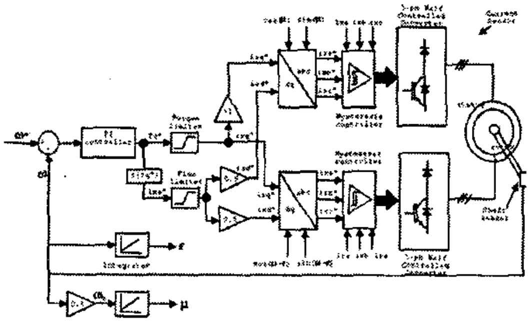


Fig. 6 Block diagram of the proposed double side control algorithm

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. 2 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 integrating it 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.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed control scheme with the half controlled power converters was studied for future implementation on a 30kW wound rotor induction machine using SABER. The simulation results with full excitation current and 25% rated load is shown in Fig. 7(i). The results at 25% load with field excitation as the function of load are shown in Fig. 7(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 8(i) and 8(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 may also be seen 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 and the switch-start method are given in Figs 9(i) and 9(ii) respectively. In contactor-start method (Fig. 9(i)) it may be seen that initially the stator was drawing the excitation current from the grid and the rotor voltages were induced due to the stator excitation and 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. 9(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 taken off and the half controlled converter is switched ON with its regular control scheme. Thus, it is demonstrated that the machine can start with both the method successfully without incurring much extra cost to the system.

V. CONCLUSION

A new double side control algorithm for a doubly fed wound rotor induction machine employing two half controlled 3-phase converters is explored in this paper. With the proposed control algorithm the machine is capable of operating for a wider speed range and the total power of the machine being shared between the stator and the rotor side converter equally, the system is capable of operating at high power range without the difficulties of paralleling the converters. In addition, by using half controlled configuration the system cost is also reduced. Splitting the excitation current equally between the stator and rotor windings and making excitation current as a function of the load current markedly improves the phase currents through the stator and the rotor and also the voltage across the DC bus. In the proposed configuration, the absolute values of the stator and the rotor frequencies are always the same and their sum is equal to the rotor shaft frequency. Thus, iron losses are minimized and the sharing of load between the stator and the rotor is always equal in our proposed algorithm, which obviously also reduces the losses in the winding and helps improving the machine utilization.

The splitting of excitation current equally between the stator and the rotor windings further reduces the KVA rating of both the machine side converters and also such arrangement is expected to reduce the overall machine and converter loss. In the proposed configuration, the power converters are shoot through safe and no dead time delay is necessary which is a distinct advantage for a system with high switching frequency. Also by using similar common emitter half controlled configuration in both the stator and rotor side, the converters do not need 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 and supports the operation of rotary transformer over the entire operating speed range. Simulation results have been shown to verify the proposed control method. The primary disadvantage of the proposed method is that the motoring mode of operation is sacrificed. However, for wind energy application that is not a serious problem since wind itself can be used for accelerating the machine.

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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

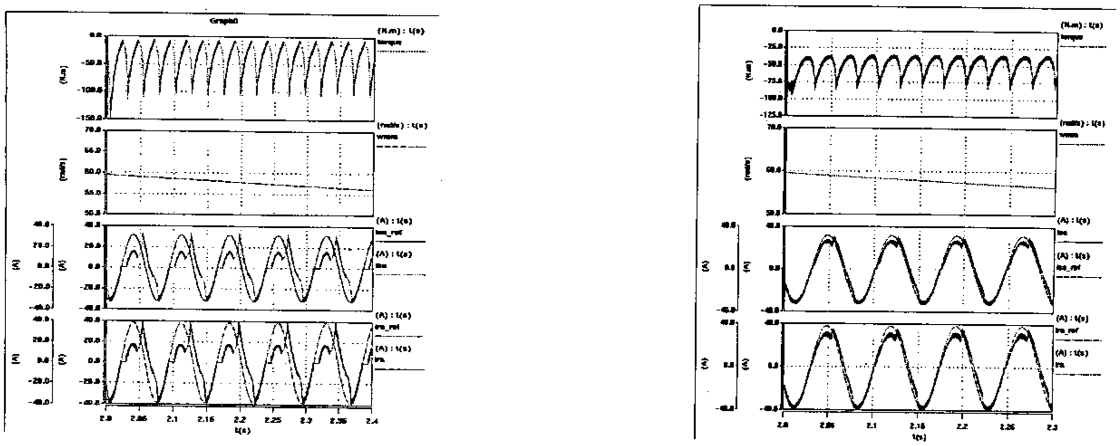


Fig. 7 Simulation results at (i) 25% load with full field excitation (LHS) , and (ii) at 25% load with filed excitation as a function of load (RHS)

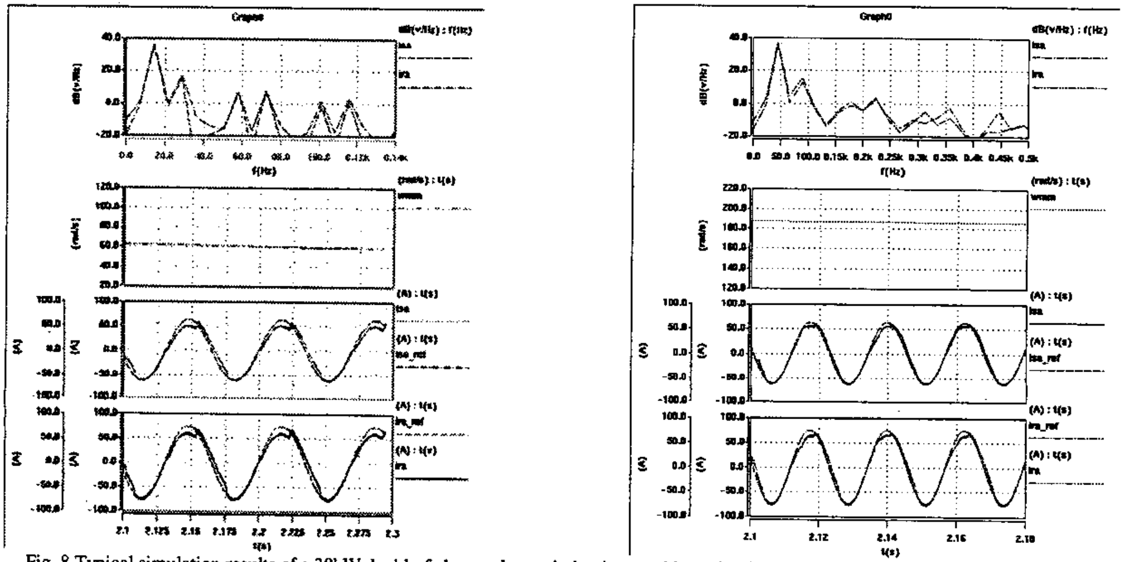
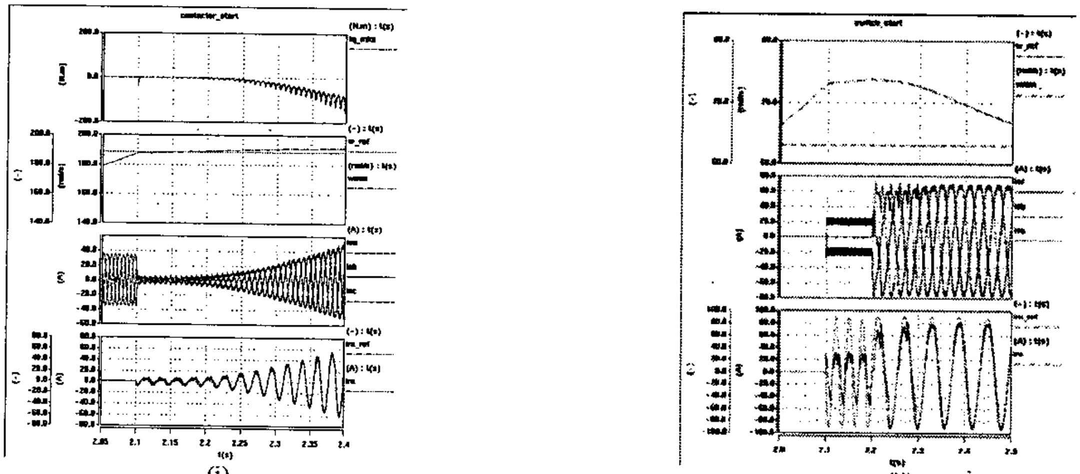


Fig. 8 Typical simulation results of a 30kW doubly-fed wound rotor induction machine: (i) with rotor shaft frequency at 30Hz (LHS) and (ii) with rotor shaft frequency at 90Hz (RHS)



(i)

(ii)

Fig. 9 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)