A Novel Control Strategy for the Rotor Side Control of a Doubly-Fed Induction Machine

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Abstract— **The prospect of using the doubly-fed induction machine (DFIM) drive for renewable energy sources like wind and wave energy has been well established. The state-of-the-art technology uses two back-to-back IGBT converters for controlling the machine and line side interface. However, IGBTs are costly compared to thyristors, especially at high power. In this paper, a novel machine side converter (MSC) and associated control strategy for the DFIM is proposed which will replace one of the IGBT converters. The proposed converter consists of a thyristor bridge and a boost/buck-boost dc-to-dc interface. This converter is capable of bidirectional power flow and thus the machine can be controlled in both the super-synchronous and sub-synchronous speed ranges. The proposed converter has the ability for successful commutation of the thyristors for all speeds of operation. Through the suitable control of the IGBT based front end converter (FEC), the composite system interfaces with the grid at nearly unity power factor. The FEC supports the power flow between the rotor circuit and the utility and in addition, it is made to work as an active filter to compensate for any additional harmonics injected by the stator of the machine to the utility. With the proposed power converter combination, the potential cost of the system is reduced without any major sacrifice in the system performance.**

I. INTRODUCTION

THE doubly-fed induction machine (DFIM) has a few distinct advantages over the conventional squirrel cage machine. The DFIM can be fed and controlled from either or both the stator and the rotor. Of the different possible combinations, rotor side control is advantageous since the power converter only needs to handle the slip power. Thus, if the machine is operated within a limited slip range, then the power converter rating can be brought down remarkably. Alternatively, if the DFIM is operated at double the rated speed, then the power extracted from the machine is doubled.

Different control strategies for the DFIM have been reported. [1], [2], [3]. Currently, several renewable energy applications such as wind or sea power generation use the DFIM, often with two back-to-back IGBT based power converters in the rotor circuit [1], [2]. IGBTs are costly compared to thyristors, especially in high power.

This paper proposes a novel power converter and the associated control strategy. The power converter consists of a thyristor bridge with a bi-directional chopper which will replace one of the IGBT inverters. The proposed power converter is expected to have a lower cost than the comparable IGBT bridge inverter while still allowing for the full four mode operation of a DFIM. The proposed converter is shown in Figure 1

A conventional IGBT based converter is used at the front end through which the rotor of the machine is connected to the line. The front-end converter controls the power flow between the rotor of the machine and the grid, and also works as an active filter for compensating the additional harmonics introduced by the stator. The complete system is made to operate at almost unity power factor. The main objective of the proposed controller is to reduce the converter cost without any major sacrifice in the performance of the system. In this paper, the whole system (machine, power converter and associated control system) is simulated in Saber and the simulation results for both sub- and super-synchronous speeds are presented.

II. BACKGROUND

Wound rotor induction machines are normally used for high power applications. Slip power recovery schemes for a wound-rotor induction machine were reported by Krämer [4] and Scherbius [5]. In both systems, the controllable electrical source used in the rotor circuit was an auxiliary machine.

With the advent of controllable power devices like thyristors, it was possible to dispense with the additional machines. In the sixties and seventies, several slip-power recovery schemes [6], [7], [8], [9] were suggested by placing a phase-controlled converter in the rotor circuit. In these schemes the overall system power factor is poor and the rotor power can flow in one direction only. Thus, the machine can operate either at sub-synchronous or at super-synchronous speeds. A cycloconverter driven DFIM control [10] permits a reversible power flow naturally and speed control is possible for sub-synchronous as well as super-synchronous operation. However, the use of cycloconverters in these applications has been restricted because of the large number of thyristors used in the power circuit.

At the present, two back-to-back IGBT inverters with a capacitive dc link [2] is the most popular choice for the rotor side control of a DFIM. However, doubly-fed machines are used at

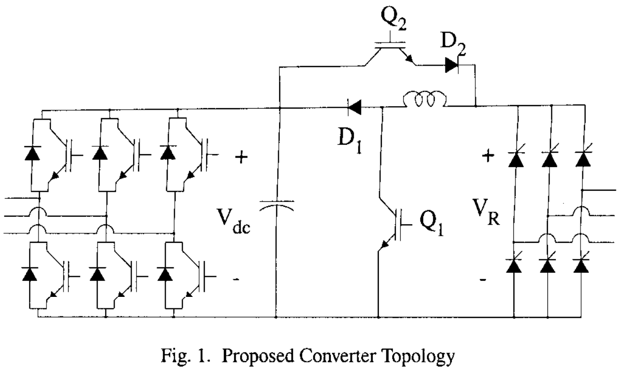

Fig. 1. Proposed Converter Topology

a higher power (few hundred kW to MW) range. In this power range, the IGBT devices become expensive, thereby increasing the system cost. Although a simple diode bridge or thyristor bridge may be a more economical choice for this power range it often reduces system performance levels.

In this paper, a new topology shown in Figure 2 comprising a thyristor bridge, a dc-to-dc chopper interface, and a line side IGBT converter, is proposed for driving a doubly-fed machine and interfacing the entire system to the grid. The proposed power converter combination, interfaces the whole system to the grid at nearly unity power factor and it controls the machine in all the four modes. The cost of the proposed converter presumably will be less than a regular three phase IGBT inverter because the rotor side power converter consists of only two IGBTs and a regular thyristor bridge. The objective of this paper is to explore the potential of this proposed power conversion system for a wind-energy application.

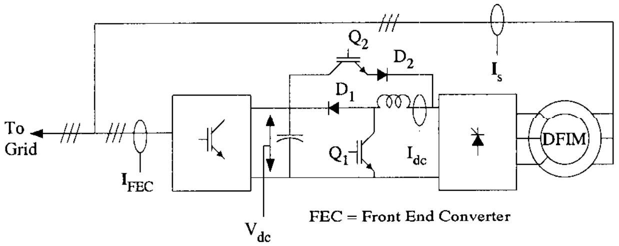

Fig. 2. System Block Diagram

III. OPERATING PRINCIPLE

The operation of the whole system can be divided into two sections — front-end line-side operation and machine-side operation as shown in Figure 3, which adds the control topology to the system block diagram. The front-end converter maintains the dc bus voltage at its rated value by controlling the power flow between the grid to the dc bus as well as maintaining the interface of the overall system to the grid at nearly unity power factor. The machine side inverter controls the speed and torque of the machine by controlling the dc link current.

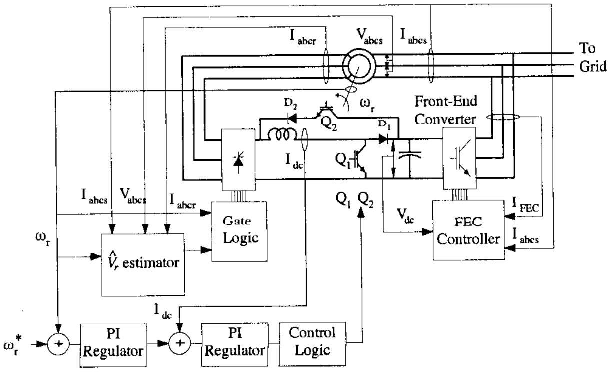

Fig. 3. Complete System Block Diagram

A. Doubly-Fed Machine Control

A *doubly-fed induction machine (DFIM)* is formed when a power converter is present in the rotor circuit of a wound-rotor induction machine. The DFIM is controlled by directing the power flow into and out of the rotor windings. Because the DFIM can operate as either a motor or a generator both at sub-synchronous and super-synchronous speeds, there are four operational modes in which the DFIM operates.

The principle of a DFIM control in these modes can be understood by the power flow diagrams given in Figures 4 to 7. In these figures, P_s is the stator power, P_r is the rotor power and P_m is the mechanical power. When the DFIM is operating as a motor in the sub-synchronous speed range (Figure 4) power is taken out of the rotor. This operational mode is commonly know as slip-power recovery. If the speed increases so that the machine is operating at super-synchronous speeds (Figure 5) then the rotor power changes direction from the sub-synchronous operation.

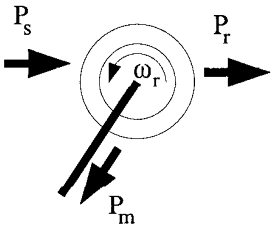

Fig. 4. Sub-Synchronous Motoring Operation

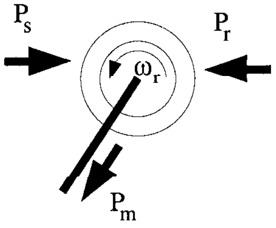

Fig. 5. Super-Synchronous Motoring Operation

When the DFIM is operating as a generator in the sub-synchronous speed range (Figure 6) power is delivered to the rotor. If the speed increases so that the machine is operating at super-synchronous speeds (Figure 7) then the rotor power

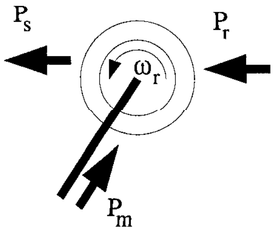

Fig. 6. Sub-Synchronous Generating Operation

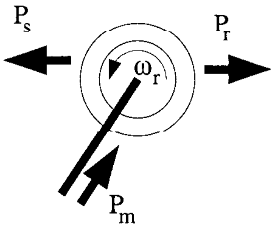

Fig. 7. Super-Synchronous Generating Operation

changes direction from the sub-synchronous operation.

Depending on the direction of power flow in the rotor circuit, the *machine-side converter* (MSC) control is divided into two operational modes — (i) Rectifier operational mode and (ii) Inverter operational mode.

A.1 MSC Rectifier Operational Mode

During sub-synchronous motoring and super-synchronous generation, the MSC will be operating in the *rectifier operational mode* since power is flowing from the rotor into the converter. Normally in this mode of operation the switch Q_2 and diode D_2 will be turned *off*. The effective circuit during this mode of operation is given in Figure 8. The link current is controlled by operating switch Q_1. The figure shows that the dc-link in this mode resembles a boost chopper, feeding from V_R to V_{dc}.

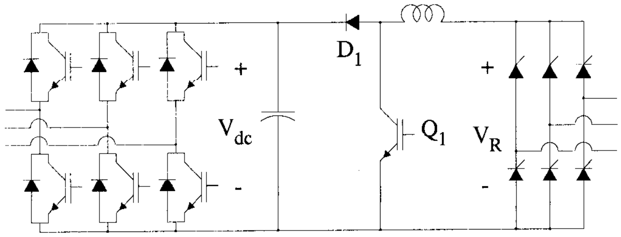

Fig. 8. MSC Rectifier Mode Circuit

A.2 MSC Inverter Operational Mode

During sub-synchronous generating and super-synchronous motoring operation the MSC will be operating in the *inverter operational mode* since power is flowing from the converter into the rotor. In this mode, the switch Q_1 will always be *on* and diode D_1 will be *off* since it is reverse biased by the dc bus voltage. Thus, the effective circuit diagram during the inverter mode of operation is given in Figure 9. The link current is controlled by modulating switch Q_2. When Q_2 is *on*, the inductor has the dc bus voltage across it which increases the inductor's current. When Q_2 is *off*, the inductor's current flows through the thyristor bridge and the machine. This circuit diagram resembles a buck-boost chopper, feeding power from V_{dc} to V_r, while V_r is negative.

Hence, the composite dc-to-dc interface may be called a *boost/buck-boost* configuration. A similar 8 switch converter topology was suggested by [11] in connection with a dc motor regenerating braking control. However, their topology does not support boost operation during the rectifier mode and it also does not operate with unipolar dc bus unlike the proposed converter topology. The unipolar dc bus is advantageous because it simplifies the front end controller.

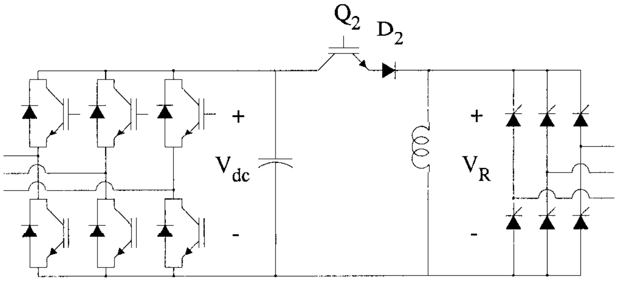

Fig. 9. MSC Inverter Mode Circuit

A.3 Mode Transitional Operation

The transition between sub- and super-synchronous operation requires a precisely timed change in direction of the rotor power flow. If the rotor power flow direction does not change at the proper time, then the machine may be unable to transition between sub- and super-synchronous (or vice versa) operation and will remain in the same speed range. This timing issue is solved for the sub- to super-synchronous operation by detecting that the system is approaching synchronous operation and then momentarily turning *off* all of the switches and allowing the wind turbine to push the generator into the super-synchronous operation.

When the transition from super- to sub-synchronous operation is desired, negative torque is required in order to decelerate the machine through synchronous speed. This negative torque must be great enough to not only overcome the positive torque from the turbine/prime mover, but also to provide the decelerating action. The challenge is that as synchronous speed is approached, the rotor voltage approaches zero and the ability to control the machine through the boost converter is lost. One solution is to detect that the synchronous speed is being approached and command the turbine pitch control to momentarily reduce the torque and allow the machine to coast down through synchronous speed. While this option works, it is undesirable because it requires control action external to the converter (turbine pitch control) and the system power output is reduced during the transition. Consequently, we are investigating an alternative approach which will allow for a controlled deceleration using only the converter action.

A.4 dc Link Control

For both speed ranges, the dc link current is approximately proportional to the torque of the machine and so the speed of the machine can be controlled by regulating the dc link current [12]. The block diagram of the dc link controller is shown in Figure 10.

The outer speed loop generates a torque command, T^*. Because the dc link inductor's current always flows in the same direction, the current command, I_{dc}^* is proportional to $|T^*|$. This current command drives the current loop consisting of a PI controller and a PWM comparator to produce the control signals for

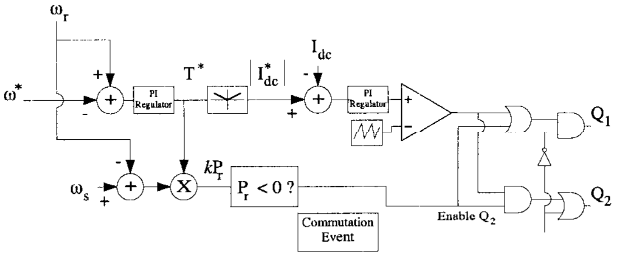

Fig. 10. dc Link Controller Block Diagram

the switches Q_1 and Q_2.

The activity of the switches Q_1 and Q_2 can be determined by the rotor power flow. When power is flowing out of the rotor, then the thyristor bridge is operated as a simple rectifier and switch Q_1 is operated to control the link current through the boost converter action. When power is flowing into the rotor, then the thyristor bridge is operated as an inverter and switch Q_2 is used to control the link current through buck-boost operation. In order to form the buck-boost topology, switch Q_1 must be kept *on*.

A.5 Commutation of Thyristors

In addition to controlling the link current during the inverter operation, Q_2 helps the thyristor bridge to commutate. This is required because the DFIM's induced rotor voltage is proportional to the slip. Consequently, as the speed approaches and reaches synchronous speed, the induced rotor voltage approaches and reaches zero volts. This means that at some speed near synchronous speed, commutation failure would occur for a conventional line commutated thyristor bridge. In the proposed converter, Q_2 provides a forced commutation action by turning *on* and reverse biasing the conducting thyristor with the dc bus voltage. During commutation, the rotor current is able to flow through the rotor-side line-to-line AC capacitors. The operation of Q_1 is unimportant for the commutation action, however, if it is kept *off* during this time then the inductor current will remain relatively constant since it will free-wheel through Q_2 / D_2. The use of Q_2 during the commutation process will assure that commutation will occur without failure even near synchronous speed.

The thyristor bridge is operated either as a rectifier or as an inverter depending on the direction of the rotor power flow. During rectifier operation, the thyristor gate signals are all asserted so that the bridge behaves like a regular diode rectifier bridge. During inverter operation, the thyristor gate signals are generated so that each upper half phase leg conducts from 210^o to 330^o of the phase voltage while the lower half phase legs conduct from 30^o to 150^o. This operation corresponds to the direct opposite of regular rectifier operation. The firing signals are derived by comparing estimated rotor voltages. The estimated rotor voltage is obtained from an observer which measures the rotor and stator current, the stator voltage and the rotor speed.

B. Front-End Controller

The converter used at the grid interface is called the *front-end converter* (FEC). The FEC employs a three-phase IGBT inverter bridge topology and is controlled to enable bi-directional power flow while keeping the dc bus voltage within good regulation. It can be operated at any desired power factor, and, hence it can act as a reactive power source. The converter is operated as a PWM voltage source inverter in the current-controlled mode; so, the harmonics in the line current waveforms are substantially reduced.

Since the DFIM's rotor is fed through a dc link chopper and thyristor bridge, the currents in the rotor will no longer be sinusoidal. These non-sinusoidal rotor currents will induce low order harmonics into the stator. Because the stator is directly connected to the grid, the grid will also see the equivalent lower order harmonics, which is not desirable.

In addition to the rotor induced harmonics, the stator may also inject reactive power into the grid. Both the reactive power and the rotor induced harmonics are taken care of by the FEC's controller. The complete block diagram of the FEC's controller is given in Figure 11. The FEC controller compensates for the power factor and harmonics by extracting the extra reactive component and harmonic components from the measured stator currents and then generating a compensating current command.

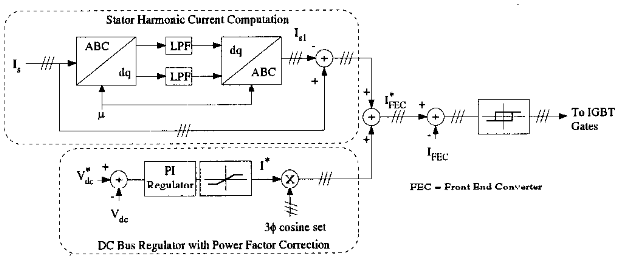

Fig. 11. Front-end Controller Block Diagram

The fundamental components of each phase current can be extracted by low pass filtering the currents in the synchronous reference frame and then returning the filtered currents to the stationary frame [13]. The harmonic and reactive components can be found by subtracting the fundamentals from the actual currents of respective phases. Hence, by adding these components to the original current reference of the FEC, the final current references are generated. A hysteresis current regulator is used to control the current loop.

IV. SIMULATION

The complete system including the doubly-fed machine model, front end converter, machine side converter and the associated control system is simulated in Saber. The Saber circuit for the machine side converter is shown in Figure 12. Real models for the semiconductor devices are used in the simulation. The machine parameters are listed in Table I.

The system is operated as a generator in both the sub-synchronous and super-synchronous modes of operation. Steady-state and transient rotor speed commands are simulated in both the sub- and super-synchronous regions. When the machine approaches synchronous speed while transitioning from the sub- to super-synchronous region, the rotor side control is momentarily disabled to allow the machine to pass through synchronous speed. Similarly, during the transition from the super-

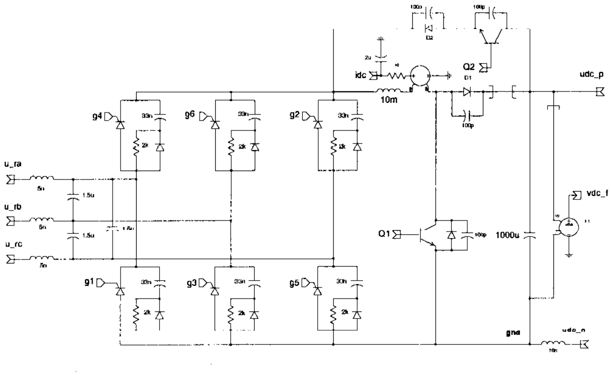

Fig. 12. Machine Side Controller Saber Circuit

TABLE I
SIMULATION MACHINE PARAMETERS

Poles	4	$f_{\text{synchronous}}$	50 Hz
P_{machine}	3kW	V_{line}	416 V_{RMS}
J_{machine}	0.1 kN-s^2	B_{machine}	0.0161 kN-s
R_s	1.557Ω	R_r	2.62Ω
X_{ls},X_{lr}	5.6549Ω	$N_s : N_r$	1:1

to sub-synchronous region, the external wind turbine pitch control is utilized to make the prime mover torque zero while both the stator and rotor are open circuited. After the machine coasts to below synchronous speed, the stator is reconnected to the grid and the rotor side control is re-enabled.

V. RESULTS AND DISCUSSION

The sample simulation results for both the sub-synchronous and super-synchronous operating modes are presented in Figures 13 through 18.

From the given results it is seen that the machine side converter controls the speed quite smoothly, while the front end converter maintains a nearly unity power factor interface with the grid. The results for both steady-state (Figure 13) and during a speed command transient (Figures 15–18) are given.

In Figure 13, the current through the front end converter, `igaa`, is not sinusoidal. This is because `igaa` has to compensate for the reactive power and harmonics introduced by the stator of the machine. The current `ia` is the system grid current and consists of the summation of `igaa` and the stator current `ias`. Notice that `ia` is nearly sinusoidal and is 180° out of phase with the grid voltage, `vas`.

Transient results showing transitions within the sub- and super-synchronous regions are given in Figure 15 to Figure 18. From the results, it may be seen that the transient results are smooth and well controlled.

Transient results showing the transition from sub-synchronous to super-synchronous operation are shown in Figure 19. In this figure, it may be seen that near synchronous speed the rotor control is disabled, the rotor phase and dc bus currents reduce to zero while the the machine accelerates only due to wind torque. This can also be observed in speed trajectory since near synchronous speed, the slope of speed trajectory is different from the rest of the acceleration period trajectory. The signal `scr_lgc` in this figure shows whether the converter is working as a rectifier (+1) or inverter (-1).

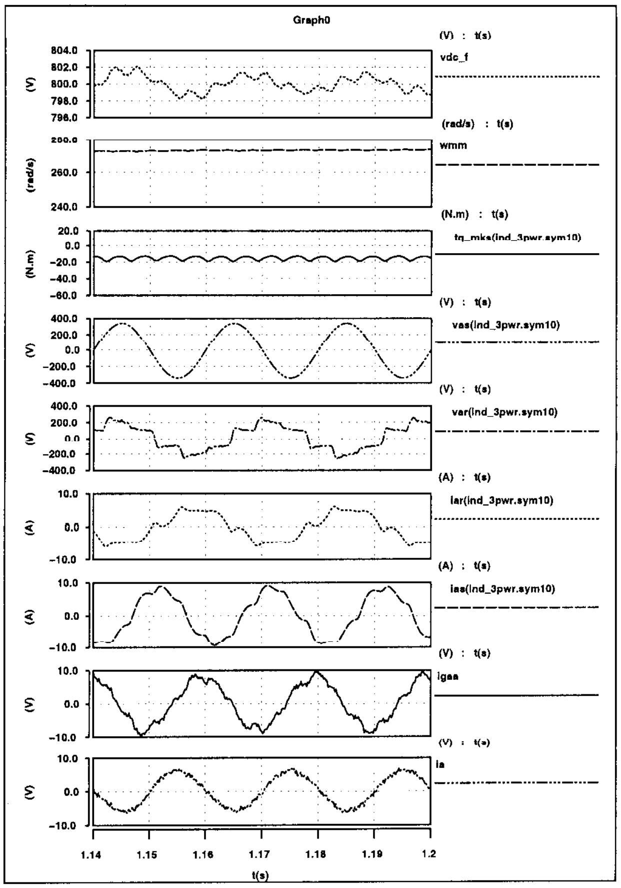

Fig. 13. Simulation Results of the Proposed Power Converter During Super-Synchronous Steady State Operation
vdc=dc bus voltage, wmm=mechanical speed,tq_mks=torque developed by the machine, vas=stator or grid voltage, v_ar=rotor phase voltage, iar=rotor phase current, ias=stator phase current, igaa=phase current through the IGBT front end converter, ia=total grid current from the front-end converter and stator of the machine

Transient results showing the transition from super-synchronous to sub-synchronous operation are shown in Figure 20. In this simulation, pitch control is used for reducing the torque at the shaft of the machine and during deceleration the stator and rotor both are disconnected from the grid so that the machine costs down through synchronous speed. In Figure 20, the signal `pitch_ctrl_en` indicates that pitch control is enabled. During this transition, since no electrical torque is produced, the deceleration time is decided solely by the mechanical time constant of the machine. This appears to be a disadvantage of the proposed converter.

The investigations of problems related to the transition between the sub- and super-synchronous region are under progress at present and will be addressed in a future publication.

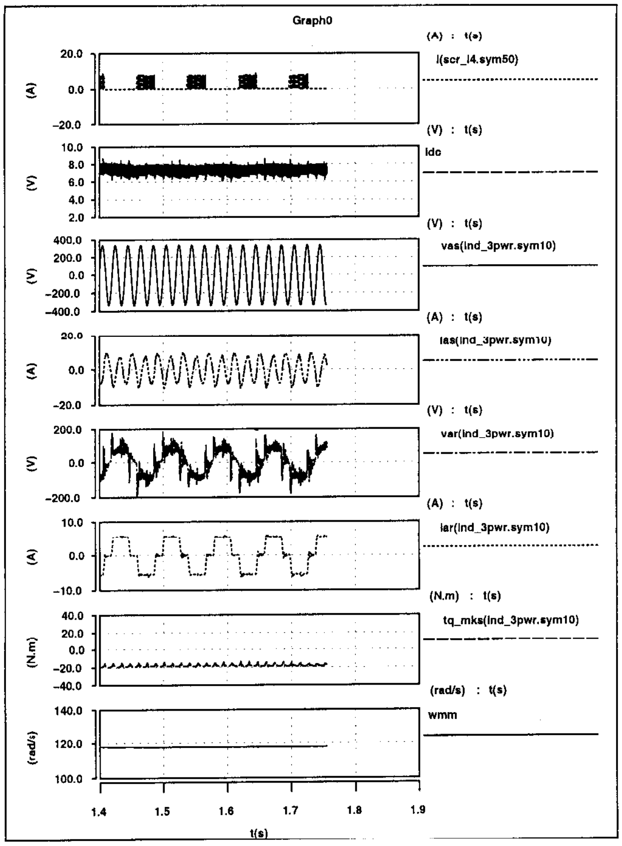

Fig. 14. Simulation Results of the Proposed Power Converter During Sub-Synchronous Steady-State Operation
i=SCR current, idc=dc Link Current, vas=stator phase voltage, ias=stator current, var=rotor phase voltage, iar=rotor phase current, tq_mks=torque developed by the machine, wmm=mechanical speed

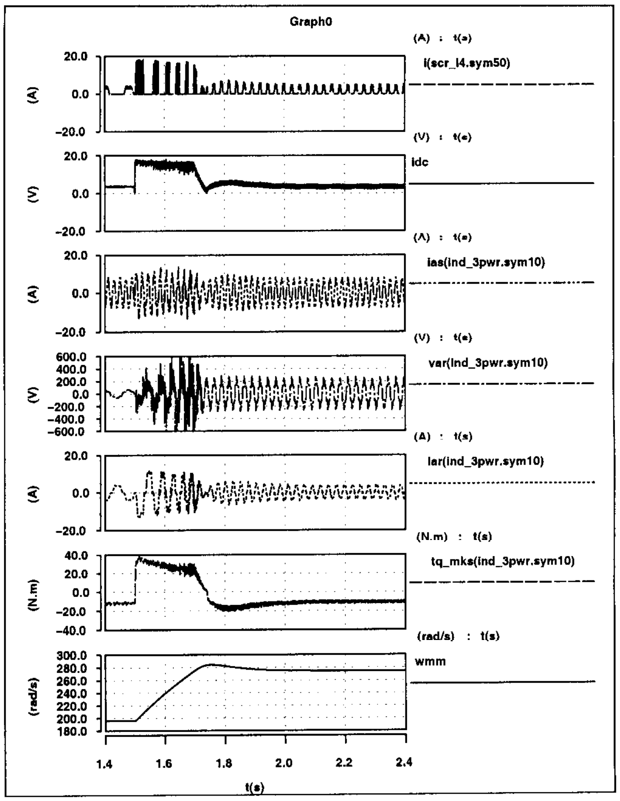

Fig. 15. Simulation Results of the Proposed Power Converter During a Super-Synchronous Transient Operation: From low to high speed
i=SCR current, idc=dc Link Current, ias=stator phase current, var=rotor phase voltage of the machine, iar=rotor phase current, tq_mks=torque developed by the machine, wmm=mechanical speed

VI. Conclusions

A new thyristorized power converter topology is proposed for the control of a doubly-fed machine. With the proposed controller, successful and reliable operation of the machine is illustrated with simulation results. Because the majority of the components of this converter are thyristors, the cost of the converter is expected to be less than a regular IGBT inverter.

The dc-to-dc chopper interface works as a boost converter during the super-synchronous generating and sub-synchronous motoring mode of operation. On the other hand, it works as a buck-boost converter during sub-synchronous generating and super-synchronous motoring mode of operation. With the buck-boost converter configuration, successful inverter operation of the thyristor bridge is obtained with a unipolar dc-link capacitor voltage. Thus, with the boost/buck-boost configuration, successful operation of all 4-modes of the machine is possible and has been illustrated through the steady-state and transient simulation results presented in this paper. The transition between sub- and super-synchronous operation is obtained through mechanical control (pitch control of turbine blade) which is sluggish in nature.

The proposed converter's thyristor bridge, unlike a traditional line commutated thyristor bridge, has ensured commutation even at synchronous speed. This is an added advantage of the proposed converter when compared to any other forced commutated thyristor bridge, since no extra commutation circuit is required.

The IGBT based front-end converter is used for controlling the power flow between the grid and the rotor of the machine as well as providing an active filter action to compensate for any additional harmonics injected by the stator of the machine. Successful near unity power factor operation of the complete system with the grid is illustrated.

The proposed power converter topology may be used for high power doubly-fed machine control in grid connected wind energy applications.

References

[1] S. W. H. de Haan, "Power electronics for renewable energy storage systems: State of the art, trends and challenges," in *Proceedings of the Power Electronics and Motion Control (PEMC)*, vol. 3, pp. 31–38, 1996.

[2] Y. Tang and L. Xu, "A flexible active and reactive power control strategy for a variable speed constant frequency generating system," *IEEE Transactions on Power Electronics*, vol. 10, pp. 472–478, July 1995.

[3] G. D. Marques, "The slip power recovery generator applied to the sea wave energy extraction," in *EPE '91. 4th European Conference on Power Electronics and Applications*, vol. 1, pp. 271–275, Litografia GEDA, 1991.

[4] C. Krämer, "Neue methoden zur regelung von asynchronmotoren und ihre anwendung für verschiedene zwecke," *Elektrotechnische Zeitschrift*, no. 31, pp. 620–625, 1908.

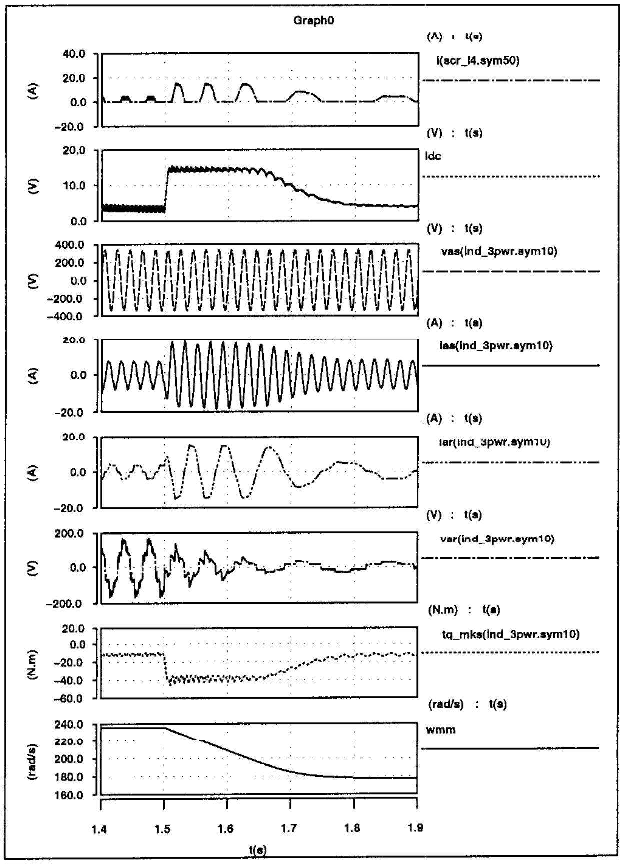

Fig. 16. Simulation Results of the Proposed Power Converter During a Super-Synchronous Transient Operation: From high to low speed i=SCR current, idc=dc Link Current, vas=stator or grid voltage, ias=stator phase current,iar=rotor phase current, var=rotor phase voltage of the machine, tq_mks=torque developed by the machine, wmm=mechanical speed

[5] A. S. Langsdorf, *Theory of Alternating-Current Machinery.* McGraw-Hill Book Company, Inc., second ed., 1955.

[6] M. S. Erlicki, "Inverter rotor drive of an induction motor," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-84, pp. 1011–1016, November 1965.

[7] A. Lavi and R. J. Polge, "Induction motor speed control with static inverter in the rotor," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-85, pp. 76–84, January 1966.

[8] W. Shepherd and J. Stanway, "Slip power recovery in an induction motor by the use of a thyristor inverter," *IEEE Transactions on Industry and General Applications*, vol. IAG-5, pp. 74–82, January/February 1969.

[9] T. Wakabayashi, T. Hori, K. Shimizu, and T. Yoshioka, "Commutatorless kraemer control system for large-capacity induction motors for driving water service pumps," in *Conference Record of the 1976 IEEE Industry Applications Conference Eleventh IAS Annual Meeting*, pp. 822–828, 1976.

[10] A. K. Chattopadhyay, "An adjustable-speed induction motor drive with a cycloconverter-type thyristor-commutator in the rotor," *IEEE Transactions on Industry Applications*, vol. IA-14, pp. 116–122, March/April 1978.

[11] D. H. Braun, T. P. Gilmore, and W. A. Maslowski, "Regenerative converter for pwm ac drives," in *IAS'91. Conference Record of the 1991 IEEE Industry Applications Conference Twenty-Sixth IAS Annual Meeting*, pp. 862–868, IEEE, 1991.

[12] P. C. Sen and K. H. J. Ma, "Rotor chopper control for induction motor drive: TRC strategy," *IEEE Transactions on Industry Applications*, vol. IA-11, pp. 43–49, January/February 1975.

[13] S. Bhattacharya, D. M. Divan, and B. Banerjee, "Synchronous frame harmonic isolator using active series filter," in *EPE '91. 4rd European Conference on Power Electronics and Applications*, vol. 3, pp. 030–035, EPE '91-Secretariat, 1991.

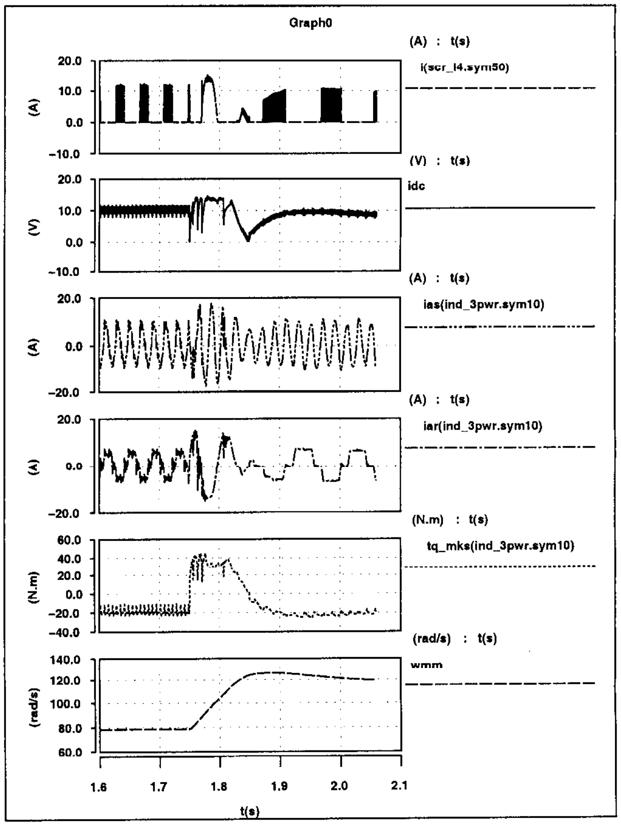

Fig. 17. Simulation Results of the Proposed Power Converter During a Sub-Synchronous Transient Operation: From low to high speed i=SCR current, idc=dc Link Current, ias=stator phase current, iar=rotor phase current, tq_mks=torque developed by the machine, wmm=mechanical speed

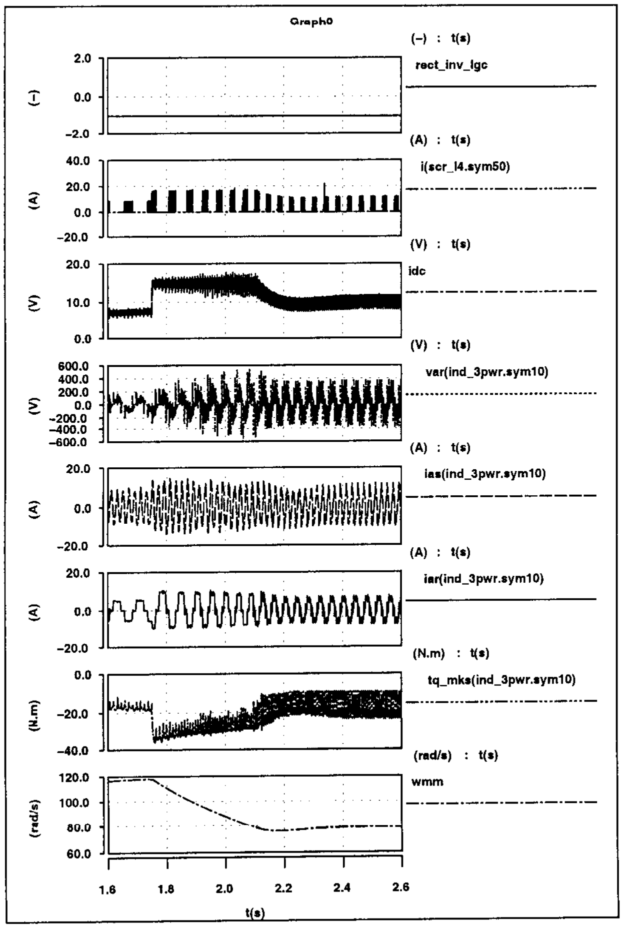

Fig. 18. Simulation Results of the Proposed Power Converter During a Sub-Synchronous Transient Operation: From high to low speed `rect_inv_lgc`=Rectifier (+1) /Inverter Mode (-1), `i`=SCR current, `idc`=dc Link Current, `var`=rotor phase voltage of the machine, `ias`=stator phase current, `iar`=rotor phase current, `tq_mks`=torque developed by the machine, `wmm`=mechanical speed of the machine.

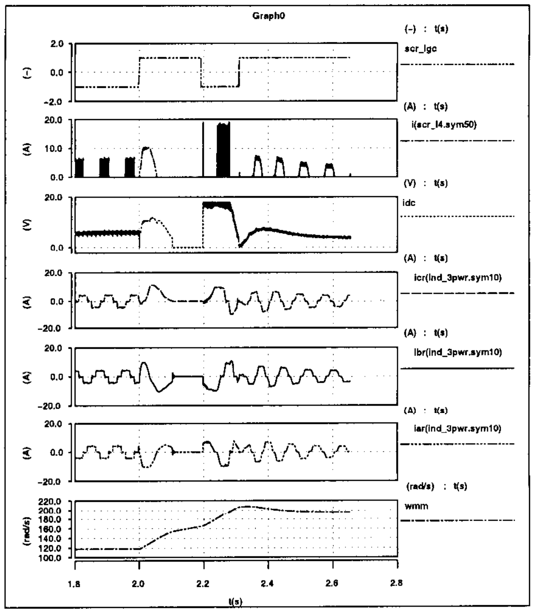

Fig. 19. Simulation Results of the Proposed Power Converter Transitioning from Sub- to Super-Synchronous Operation `scr_lgc`=Rectifier (+1) /Inverter Mode (-1), `i`=SCR Current, `idc`=dc Link Current, `icr`=rotor phase C current, `ibr`=rotor phase B current, `iar`=rotor phase A current, `wmm`=mechanical speed

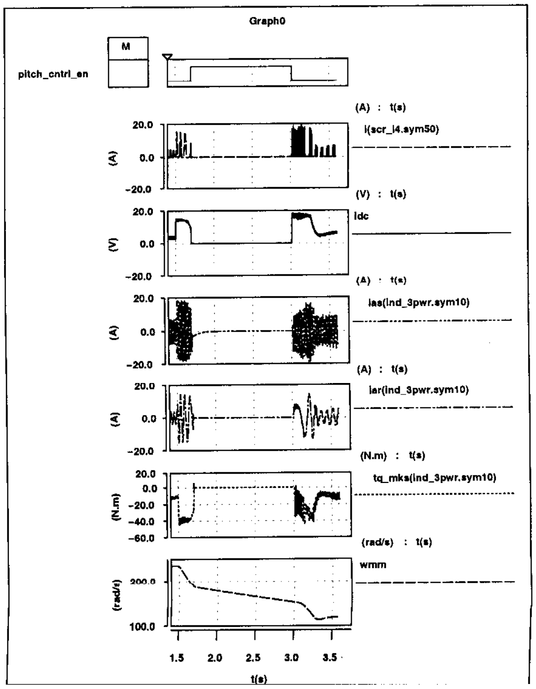

Fig. 20. Simulation Results of the Proposed Power Converter Transitioning from Super- to Sub-Synchronous Operation `pitch_cntrl_en`=Rotor pitch control (+1) / Converter Control (0), `i`=SCR Current, `idc`=dc Link Current, `ias`=stator phase current, `iar`=rotor phase A current, `wmm`=mechanical speed