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A New Topology of Speed Control And Power Factor Improvement of A Novel Induction Machine with Converter Fed Rotor

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Abstract: This project investigates a novel induction machine topology that uses a rotating power electronic converter. The stator is Y connected and directly connected to the grid, while the rotor windings are open-ended and fed by a back-to-back converter with a floating capacitor. Dynamic performance of the potential of improving its efficiency and power factor is investigated. The topology is referred to as wound rotor induction machine with rotating power electronic converter topology offers the possibility to magnetize the induction machine from the rotor side by introducing a reactive voltage in the rotor. Thus, the power factor of the machine can be improved. Constant speed variable load operation can be achieved by setting the frequency of the introduced voltage. Power factor and efficiency improvements of the induction motor are studied with different settings of phase-shift angle between the two converters. Moreover, the dynamic performance of the induction machine is explored in MATLAB/Simulink simulation results at a constant speed, variable load operation of the induction machine is obtained by setting the frequency of the rotor voltage.

Keywords: Back-To-Back Converter, Induction Machine Drives, Open-End Winding, Unity Power Factor, Dynamic Performance.

I. INTRODUCTION

A dual-stator winding topology is studied for power factor improvement. In this topology the stator has two sets of electrically isolated windings of the same or dissimilar phase. The main stator winding is connected to the grid directly or via a converter while the auxiliary winding is fed by a converter. Power factor improvement is achieved by introducing a proper capacitance to the circuit through the auxiliary winding. Moreover, the auxiliary stator winding can be removed while its converter can be moved to the other end of the main winding terminals, which means that the stator winding is open-ended. The results show that this topology has good performance on power factor improvement where the SCIM is capable of operating at unity and leading power factor. However, converter and capacitor in these topologies have to be dimensioned for rated voltage to ensure that the machine can operate over the full load range up to the rated load. Furthermore, the induction machine can be magnetized from the rotor side of a wound rotor induction machine (WRIM). This is usually used in doubly-fed induction machine (DFIM) topologies. This topology is capable of controlling the active and reactive power thereby the power factor. However, it requires closed loop control with the exact position information of the flux. Though the WRIM enables the access to the rotor winding to give better speed and power factor regulation, reliability of the machine is reduced while the maintenance cost is increased due to the slip rings and carbon brushes. Carbon brushes and slip rings employed in WRIM have limited lifespan because of their mechanical contact thus they need to be replaced by new ones from time to time. Moreover, the carbon dust has a negative impact on the machine insulations.

Consequently, the maintenance cost of the WRIM is increased while the reliability is decreased. Brushless WRIM is therefore another interesting topic for research. Topology using two cascaded induction machines is one of the brushless devices. However, the torque-speed characteristic becomes distorted as the synchronous speed is dependent on the combination of the pole numbers of the two machines. A rotary transformer topology is developed, in which a rotating transformer is mechanically and electrically coupled to the rotor of the WRIM. This topology enables the control of the speed, current, torque and power factor of the WRIM. However, the machine becomes large and bulky. A topology using a rotor-integrated-converter is studied where a compact rotor design is obtained. Futhermore, the concept of applying a rotating power electronic converter in DFIG is also presented. As an alternative, a topology of wound rotor induction machine with a rotating power electronic converter (WRIM-RPEC) is investigated in this thesis. This topology was invented by Magnus Lindmark. It is proposed to magnetize the induction machine from the rotor side by connecting a converter to the rotor. It offers advantages overcoming two of the major drawbacks of the conventional WRIM; poor power factor and low reliability due to the use of carbon brushes and slip rings.

The stator of the WRIM is directly connected to the grid while the rotor windings are either open-ended or Y-connected. The open-ended rotor windings can be fed by dual two-level three-phase converters connected in back-to-back configuration. Otherwise single two-level three phase converter can be connected to the Y-connected rotor windings. The converter together with its controller is proposed to be integrated in the rotor or its shaft and to rotate with it. In this paper, the impact of changing the phase-shift angle between the two back-to-back connected converters on power factor improvement is further studied. Efficiency improvement for the induction machine as well as the whole system is also studied. Moreover, dynamic performance of the induction machine including starting, loading and load changing is investigated through simulation results.

II. SYSTEM MODELING

The WRIM-RPEC system using the back-to-back converter configuration is shown in Figure 1. As can be seen, the stator is directly connected to the grid while the open-ended rotor windings are fed by dual two-level three-phase converters. Each terminal of the open-ended rotor windings is connected to a converter. These two converters are connected in back-to-back configuration by sharing a floating dc-link capacitor. There is no additional power source over the dc-link. The configuration of the back-to-back converter is shown in Figure2. The back-to-back converter together with its controller can be integrated with the rotor or its shaft and rotate with it.

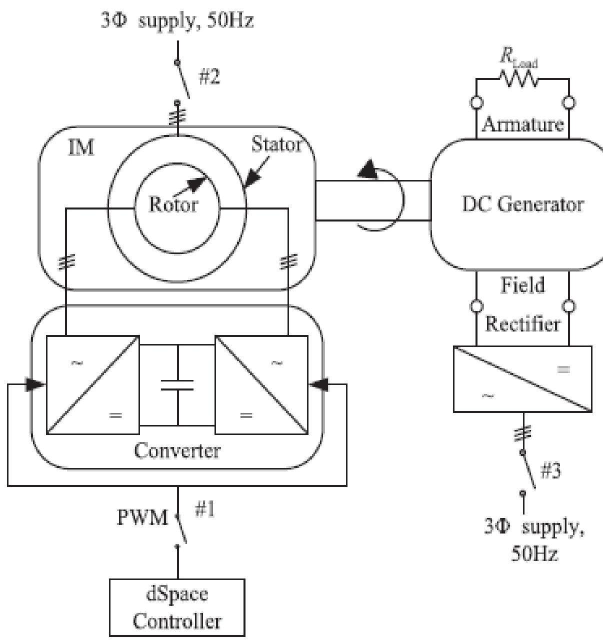

Fig.1. Configuration of the system.

The control could be achieved via wireless communication. In this way, slip rings and carbon brushes of the wound rotor induction machine can be removed thereby reducing the cost from the frequent maintenance that is otherwise required. Moreover, the back-to-back converter in Figure1 can be replaced by a single two-level three-phase converter. In this case, the rotor windings are Y-connected. The switching signals are divided into two groups, one for each converter. Sinusoidal SPWM strategy is applied to the two voltage source converters with the same switching frequency and modulation index. The phase-shift angle, θps, between the two converters can be varied from -180^0 to $+180^0$. A zero θps means that the rotor windings are short-circuited. θps = $\pm180^0$ means that full voltage is supplied. The dc-link voltage of the converter is not controlled but automatically balanced depending on the speed and load of the induction machine.

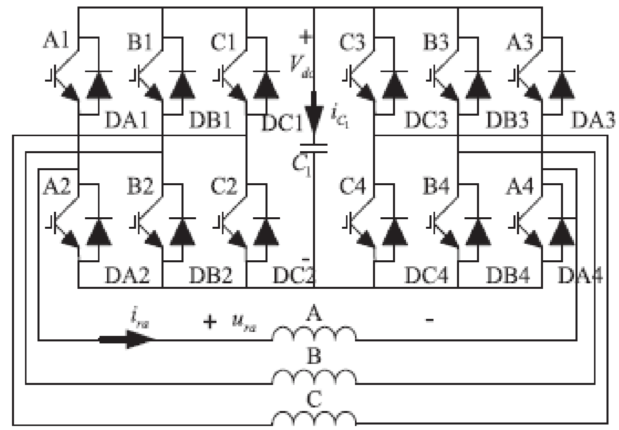

Fig. 2. Connection of the back-to-back converter to the rotor windings.

The flux generated in the stator will induce ac currents in the rotor windings. In the beginning, even though the switching signals are available, the valves cannot conduct since the dc-link voltage is zero. These currents can only flow through the anti-paralleled diodes thereby charging the capacitor. The level of capacitor voltage will depend on the phase-shift angle θps between the two converters. If θps = 0^0, the capacitor cannot discharge through the IGBTs and its voltage will rise to a very high level. In contrast if θps = 180^0, the capacitor voltage will be low which however makes it difficult to magnetize the machine from the rotor side. In this paper θps = 60^0 is used during the start of the machine. In addition, the high starting rotor current will rapidly discharge the capacitor during the acceleration of the induction machine. Thus, the capacitor voltage cannot be maintained and the converter is unable to supply a voltage of constant frequency to the rotor windings. This topology is applicable to all induction machines with open-end rotor windings regardless of the power rating of the machine. Constant speed variable load operation is possible within a speed and load range that depends on the size, pole number and cooling of the machine. It is also possible to run the machine at low speed under light load conditions. Moreover, this configuration has potential as a brushless topology if the converter together with the controller can be integrated in the rotor replacing the carbon brushes and slip-rings.

III. SIMULATION RESULTS

Dynamic performance of the presented induction machine, including starting, loading and load changing, are investigated through simulation.The simulated and measured results including speed, capacitor voltage and currents in the rotor and the stator are shown in Figs. 4, respectively. The reference speed signals is set to 1400 r/min by controlling the fundamental frequency of IGBTs at 3.3 Hz from t = 0 s.

A similar starting procedure is applied both in the simulation. The dynamic performance of the presented system is explored using MATLAB/Simulink. The Simulink model shown in Fig.3 mainly consists of a wound rotor induction machine, a three-phase voltage source, a mechanical load source, two back to back connected converters fed by a PWM generation block.

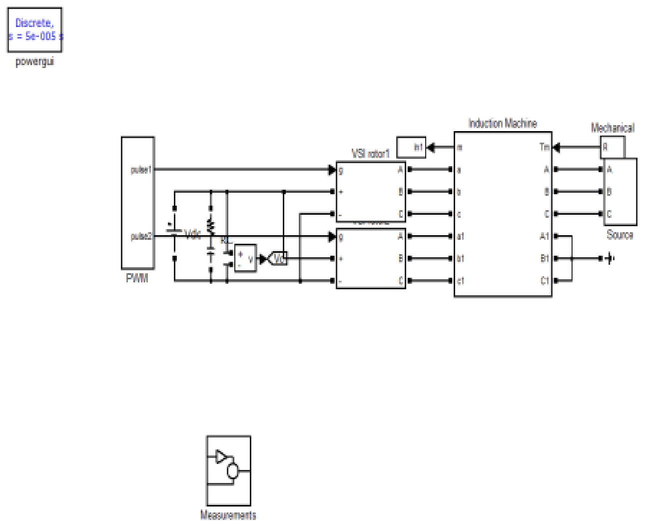

Fig. 3. Simulation diagram.

As can be seen in Fig4, a resistor is paralleled with the dc-link capacitor. In reality this resistor is connected in the converter for the reason of safety to protect the capacitor from unwanted transients. It is also considered in simulation.

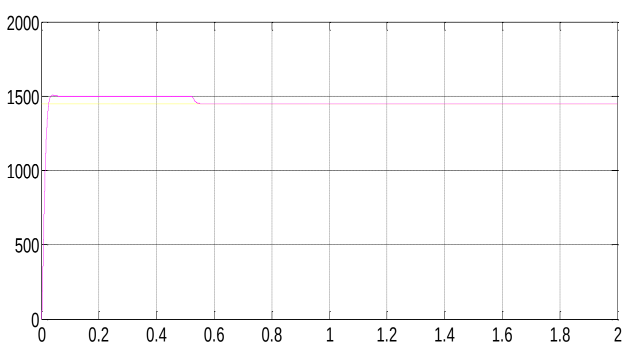

Fig 4(a). Speed

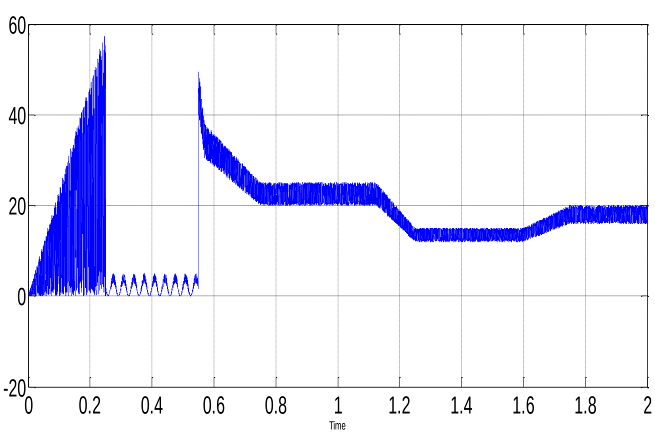

Fig 4(b). Capacitor voltage.

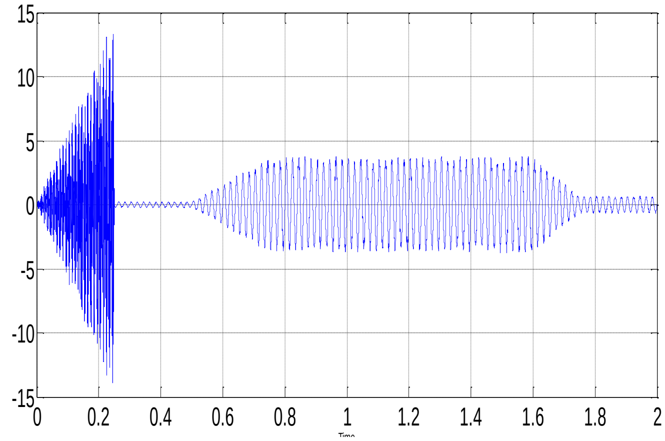

Fig 4(c). Rotor current of Phase A.

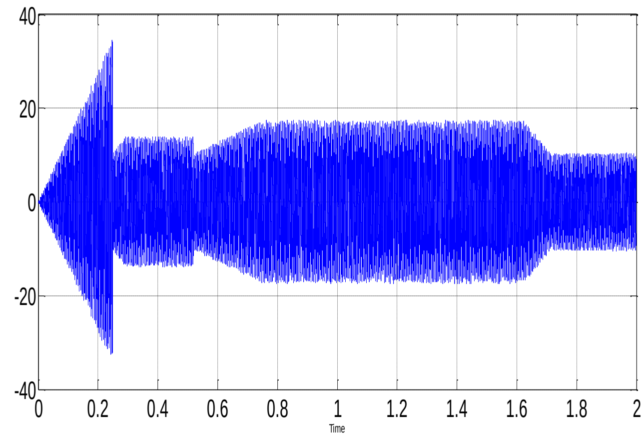

Fig 4(d). Stator current of Phase A.

Fig.4. Simulation results for the dynamic performance of the system.

In the simulation results shown in Fig. 4 the supply voltage is ramped from t = 0s to t = 4s at no load with θ_{ps} = 60◦. The dc-link capacitor voltage is oscillating during the acceleration and the maximum value is 57V approximately. The machine accelerates to the no-load speed within around 3 s and stabilizes at the no-load speed without following the reference speed. The capacitor voltage during startup is unstable and the converter is therefore unable to provide a sufficient voltage at the frequency of 3.33 Hz to the rotor windings. The starting currents in the rotor and stator gradually rise to their maximum values, 16.5 and 34 A (peak), respectively. Note that peak values are used in following if not defined otherwise. When the speed becomes stable, the capacitor voltage declines rapidly and oscillates between 0 and 5 V due to the low no-load rotor current. The rotor current at no load steady state is 0.5A to overcome the friction. The stator current decreases to around 5A when the rotor reaches the no-load speed but gradually rises to 9A as full voltage is applied. At t = 10 s, the load torque is ramped up from 0 to the rated value of 12.3N·m within 5 s. During this period the rotor current increases and charges the capacitor. At t = 11.4 s the capacitor voltage is increased to its peak value of 49 V and then stabilizes to 25.7 V after t = 15 s. As θps = 60◦, the converter supplies a voltage to the rotor windings.

The frequency of the voltage is set to 3.33 Hz thus the speed is synchronized to 1400 r/min at around t = 12s before full load is applied. Meanwhile, the stator current rises at first but has a dip at around t = 11.5 s before it gets stable. The dip can also be seen in the measurements at around t = 13 s in Fig. 4(d). At t = 22 s, θps is ramped from 60◦ to 180◦ in 3 s. The capacitor voltage falls to 13.2 V and keeps oscillating with a ripple of 8 V, while the speed is kept the same. This can be seen in both the simulations and measurements. When the capacitor voltage decreases, the stator current at rated load increases from 11 to 11.8 A which are 77% and 83% of the rated current. This implies the stator power improvement of the induction machine. At t = 31 s, the load torque is reduced gradually from the rated value to 0. It can be seen that even though the rotor current is decreased, Fig. 4(c), the capacitor voltage increases since the voltage drop on the rotor winding is reduced with the reduced current. In addition, the stator current decreases but rises again to 7.8 A after t = 34s, Fig. 4(d). This no-load current is lower than the current between the period 4–10 s, which is also at no load. This is because the capacitor voltage after t = 34 s is around 20 V and the induction machine is then magnetized from the rotor side. Therefore the required stator current becomes less. Meanwhile it can be noted that the speed of the induction machine is kept the same during the load torque decrease. This implies that the induction machine with the rotor fed by a converter is capable to operate at constant speed and variable load.

IV. CONCLUSION

In the presented induction machine with converter-fed rotor windings, the stator power factor can be effectively improved within a wide load range. Correspondingly, the efficiency of the induction machine is increased. The efficiency is further improved considering the losses in the power distribution network. Results for the dynamic performance including starting, loading and deloading of the induction machine are presented from simulation. It shows that the induction machine is capable of operating at constant speed and variable load by setting the fundamental frequency of the converter. The dc-link capacitor voltage is considerably low which implies a significant reduction of capacitor and converter size.

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