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A Modular Multilevel Cascaded Inverter based on double star chopper cell for Speed Sensor less Startup of an Induction Motor

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Abstract:-*This paper gives theoretical and experimental consideration on a practical speed-sensor less start-up method for an induction motor driven by a modular multilevel cascade inverter based on double-star chopper cells from standstill to middle speed. This motor drive is suitable, particularly for a large-capacity fan- or blower-like load. The load torque is proportional to a square of the motor mechanical speed. The start-up method is characterized by combining capacitor-voltage control with motor-speed control. The motor-speed control with the minimal stator current plays a crucial role in eliminating a speed sensor from the drive system and in reducing an a voltage fluctuation occurring across each dc capacitor. Experimental results obtained from the 400-V 15-kW downscaled system with no speed sensor verify that the motor-speed control proposed for the DSCC-based drive system can enhance the start-up torque by a factor of three under the same ac-voltage fluctuation. Several start-up waveforms show stable performance from standstill to middle speed with different load torques.*

Keywords:-*Medium-voltage induction motor drives, minimal stator current, modular multilevel cascade inverters, speed sensor less start-up method.:*

I. INTRODUCTION

Attention has been paid to medium-voltage motor drives for energy savings without regenerative brakes, A modular multilevel cascade inverter based on double star chopper cells (MMCI-DSCC) has been expected as one of the next-generation medium-voltage multilevel pulse width modulation (PWM) inverters for such motor drives For the sake of simplicity, the MMCI-DSCC is referred to as the “DSCC” in this paper. Each leg of the DSCC consists of two positive and negative arms and a center-tapped inductor sitting between the two arms. Each arm consists of multiple bidirectional dc/dc choppers called as “chopper cells.” The low voltage sides of the chopper cells are connected in cascade, while the electrically floating high-voltage sides of chopper cells are equipped with a dc capacitor and a voltage sensor. A synergy effect of lower voltage steps and phase-shifted PWM leads to lower harmonic voltage and current, as well as lower EMI emission, as the count of cascaded chopper cells per leg increases. The power conversion circuit of the DSCC is so flexible in design that any count of cascaded chopper cells is theoretically possible When a DSCC is applied to an ac motor drive, the DSCC would suffer from ac-voltage fluctuations in the dc-capacitor voltages of each chopper cell in a low-speed range, because the ac-voltage fluctuation gets more serious as a stator-current frequency gets lower. Hence, the fluctuation should be attenuated satisfactorily to achieve stable low-speed and start-up performance. Several papers have exclusively discussed startup methods for DSCC-based induction motor drives

The aim of this paper is to verify the effectiveness and practicability of a speed-sensor less start-up method for a DSCC based induction motor drive, in which the motor starts rotating from standstill to middle speed with a ramp change. This motor drive is suitable, particularly for an application to a fan-or blower-like load. The load torque is proportional to a square of the motor mechanical speed , and is changing slow enough to be considered as steady-state conditions. The start-up method discussed in this paper is characterized by combining capacitor voltage control with motor-speed control. The capacitor-voltage control plays a part in regulating the mean dc voltage of each of the dc capacitors and in mitigating the ac voltage appearing across each dc capacitor, which fluctuates at the stator-current frequency. The motor-speed control makes it possible to eliminate a speed sensor from the drive system and to mitigate the ac-voltage fluctuation in all the frequency range. This motor-speed control relies on an equivalent circuit of an induction motor,. It is somewhat similar in basic idea to conventional “volts-per-hertz” or shortly “*V/f*” and “slip-frequency” control techniques, but different in terms of combining the two control techniques together. The motor-speed control is based on “feedback” control of the stator current, which is the same as that in the slip-frequency control, whereas the commands for the amplitude and frequency of the stator current are based on “feed forward” control in consideration of a speedversus-load-torque characteristic, as done in the *V/f* control. Therefore, neither motor parameter nor speed sensor is required. Furthermore, the motor-speed control is applicable to any inverter equipped with current sensors at the ac terminals.

II. CIRCUIT CONFIGURATION AND CAPACITOR VOLTAGE CONTROL

Fig. 1 shows the main circuit configuration of the DSCC The center tap of each inductor is connected directly to each of the stator terminals of an induction motor, where iu is the *u*-phase stator current. The center-tapped inductor is more cost effective than two non coupled inductors per leg, because the center tapped inductor presents inductance *LZ* only to the circulating
Current *iZ* and no inductance to the stator current iu. It brings significant reductions in size, weight, and cost of the magnetic core.1 These advantages in the center-tapped inductor are mostly welcomed, particularly applications to motor drives, in which no ac inductors are required between the motor and the inverter.

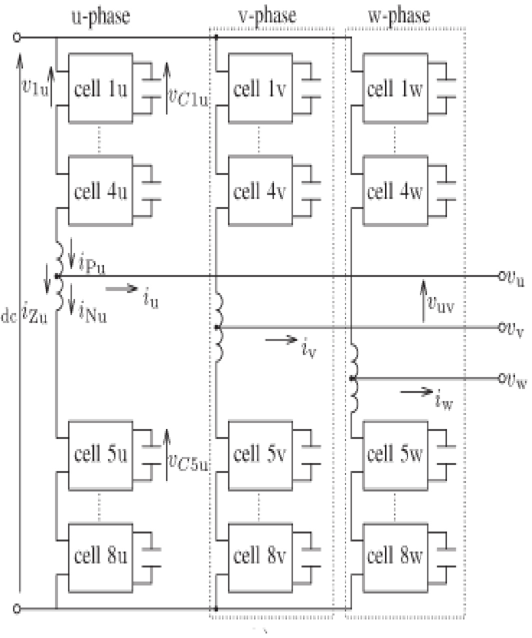

Fig. 1.Circuit configuration for an MMCI-DSCC Power Circuit

In Fig. 1, instantaneous currents *i*Puand *i*Nuare the *u*phase positive- and negative-arm currents, respectively, and *i*Zu is the *u*-phase circulating current defined as follows

$$i_{Zu} \triangleq \frac{1}{2}(i_{Pu} + i_{Nu})$$

Note that *i*Zu includes dc and ac components to be used for the capacitor-voltage control. The dc component flows from the common dc link to each leg, while the ac component circulates among the three legs. The individual ac components included in the three-phase circulating currents ˜*i*Zu, ˜*i*Zv, and ˜*i*Zw cancel each other out, so that no ac component appears in either motor current or dc-link current. The arm currents *i*Pu and *i*Nu can be expressed as linear functions of two independent variables iu and *i*Zu as follows

$$i_{Pu} = \frac{i_u}{2} + i_{Zu}$$
$$i_{Nu} = -\frac{i_u}{2} + i_{Zu}$$

III. MOTOR SPEED CONTROL

This section describes a motor-speed control forming a feedback loop of three-phase stator currents for achieving a stable start-up of an induction motor. First, the motor-speed control is discussed in terms of a form and function. Second, it is compared with conventional motor-speed control techniques, i.e., “volts-per-hertz” and “slip-frequency” control techniques.

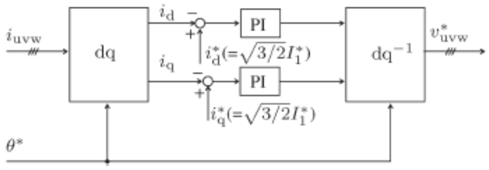

Fig. 2.Block diagram for the motor-speed control based on a feedback control of the stator current

The motor-speed control forms a feedback loop of three phase stator currents to realize a stable start-up from standstill. This requires the current sensors attached to the ac terminals. The stator current in one phase is calculated by the corresponding arm currents detected. Therefore, no additional current sensor is required Fig. 3 shows the block diagram for the motor-speed control. The three-phase stator currents are transformed into dc. quantities by using the $d-q$ transformation to enhance current controllability. In Fig. 3, $\theta*$is the phase information used for the $d-q$ transformation, whereas *i***d* and *i***q* are the command currents given by

$$i_d^* = i_q^* = \sqrt{\frac{3}{2}}I_1^*$$

where*I**1 is the command for the stator rms current.

Note that*I**1 and *f**are given not by feedback control

IV. COMPARISONS OF THREE MOTOR-SPEED CONTROL TECHNIQUES

The “volts-per-hertz” control or shortly “*V/f*” control has two independent variables *V*1 and *f*, in which *V*1 is the stator voltage and *f* is the stator frequency. On the other hand, the two dependent variables are the stator current *I*1 and the slip frequency fs. The *V/f* control is a straightforward speed control requiring no speed sensor, which is based on feed forward control of $V1$ and f. However, both motor and DSCC may suffer from an overcurrent during the start-up or when a rapid change in torque occurs. The slip-frequency control has two independent variables $I1$ and fs, and the two dependent variables are $V1$ and f. Here, the commands for $I1$ and $fs$are determined by a feedback loop of the motor mechanical speed, thus requiring a speed sensor attached to the motor shaft. The slip-frequency control can provide a faster torque response than the V/f control because of the existence of a feedback control for the motor mechanical speed.

The motor-speed control proposed for the DSCC-based induction motor drive has two independent variables $I1$ and f, and the two dependent variables are $V1$ and fs. Unlike the slip frequency control, the motor-speed control requires no speed sensor because the commands for $I1$ and f, i.e., I^*1 and $f*$, are given not by feedback control, but by feed forward control, as done in the V/f control. This implies that the motor speed control proposed in this paper is inferior to the slip frequency control, in terms of torque controllability. However, it is applicable to a fan- or blower-like load, where the load torque is changing relatively slow and predictable. Moreover, no overcurrent occurs during the start-up, or when a rapid change in torque occurs, because of the existence of a feedback control loop of the stator current. An energy saving during a start-up does not make a significant contribution to total energy saving performance from a practical point of view because the motor power in a low speed range is negligible in applications such as fan- or blower-like loads. This means that a comparison of the three methods, in terms of energy saving performance during a start-up, does not make sense when fan- or blower-like loads are considered. Moreover, current stresses of the conventional motor-speed control techniques, the V/f and slip-frequency control, and the proposed motor-speed control technique are the same, at least, in a steady-state condition when a magnetizing current is set to the same value in all speed range

V. COMMAND STATOR CURRENT

The following practical limitations should be imposed on I^{*1}

- I^*1 should take the smallest current to produce a desired
- motor torque TM. The maximum value of each arm current is lower than the

amplitude of the rated stator current. The first condition should be met because as I^*1 gets larger, $\Delta vCju$ gets higher, as predicted from In other words, minimizing $I*1$ enables minimization of $\Delta vCju$. The second limitation should be met because an increase in the arm currents brings additional loss to a DSCC and makes the center-tapped inductors larger and heavier. Note that such an increase in the arm currents occurs particularly in low-speed operation,

where a large amount of ac circulating current is superimposed on each arm current. The ac circulating current superimposed results in mitigating the ac-voltage fluctuation appearing across the dc capacitor of each chopper cell. Hence, I^*1 should be minimized because the ac component of the arm current is proportional to I_1^*.

$$T_M - T_L > (J_M - J_L)\frac{d\omega_{rm}}{dt}$$

whereTL is the load torque, JM is the moment of inertia of the motor, JL is that of the load, and $\omega rm$is the mechanical angular velocity. The right-hand term on (11) corresponds to an acceleration torque for the start up. These three assumptions are applicable to fan- or blower-like loads for the following reasons. The first assumption is valid because the motor frequency, or the motor mechanical speed, is adjusted slowly, e.g., spending a few or several minutes to complete its start-up procedure. The second assumption is reasonable for an induction motor. The third assumption is valid because JL is typically 50–100 times larger than JM

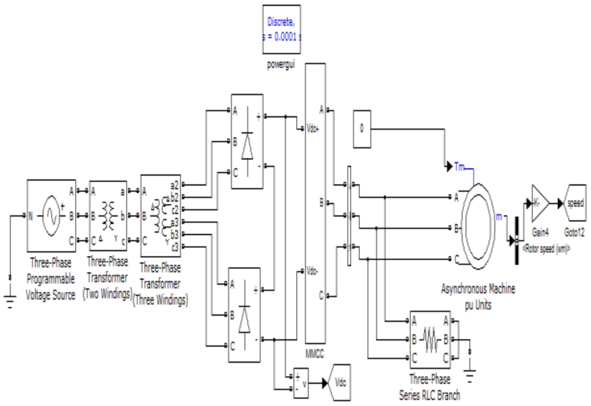

Fig. 3. Simulation model

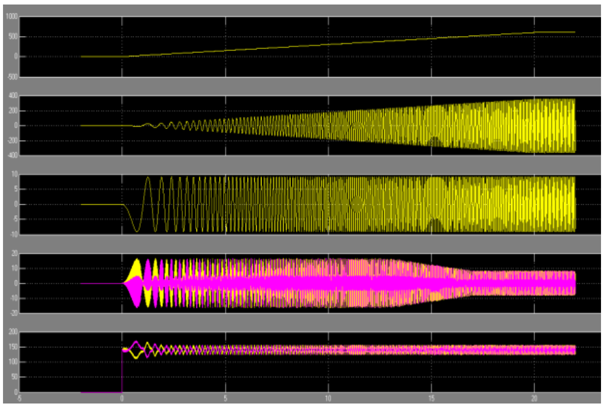

Fig. 4. Experimental start-up waveforms when *I*1∗= 6.4 A (20%) and *TL* = 0%, where *I*0 = 6.4 A (35%).

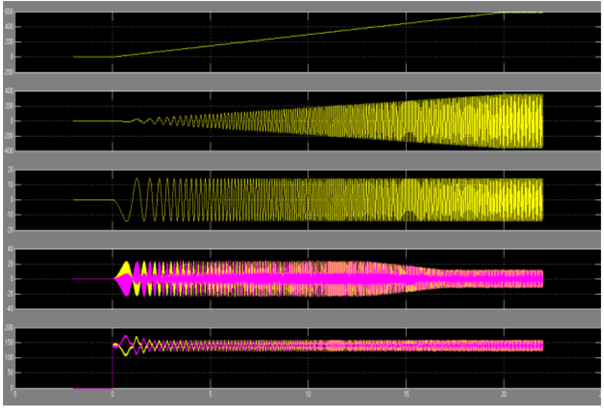

Fig. 5. Experimental start-up waveforms when I1∗ = 10 A (31%) and TL = 20%, where I0 = 7.0 A (38%).

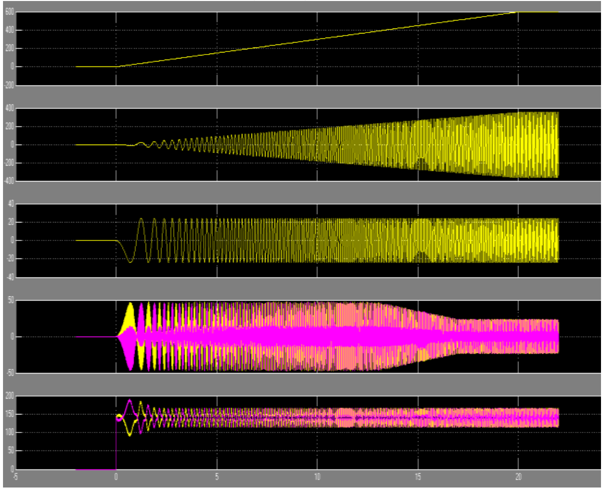

Fig. 6. Experimental start-up waveforms when I1∗ = 17 A (5 3 %) and TL = 20%, where I0 = 16.6 A (90%).

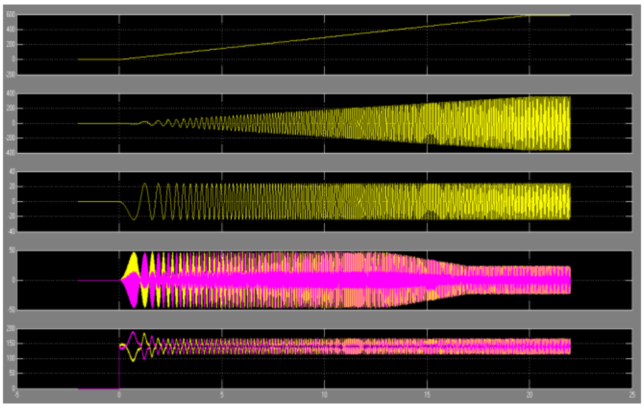

Fig. 7. Experimental start-up waveforms when I1∗ = 14 A (44%), and TL = 40%, where I0 = 9.9 A (54%).

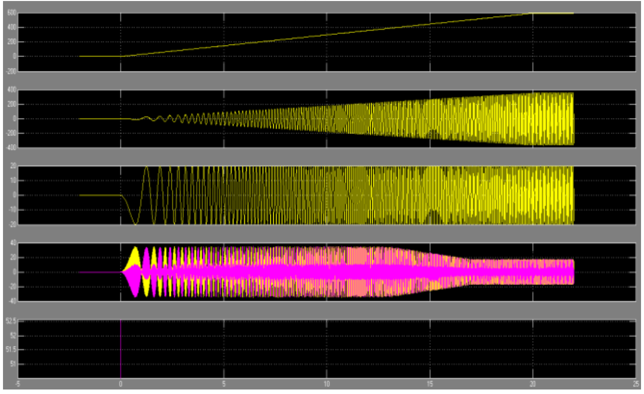

Fig. 8. Experimental start-up waveforms when I1∗ = 17 A (53%), and TL = 60%, where I0 = 12.0 A (65%).

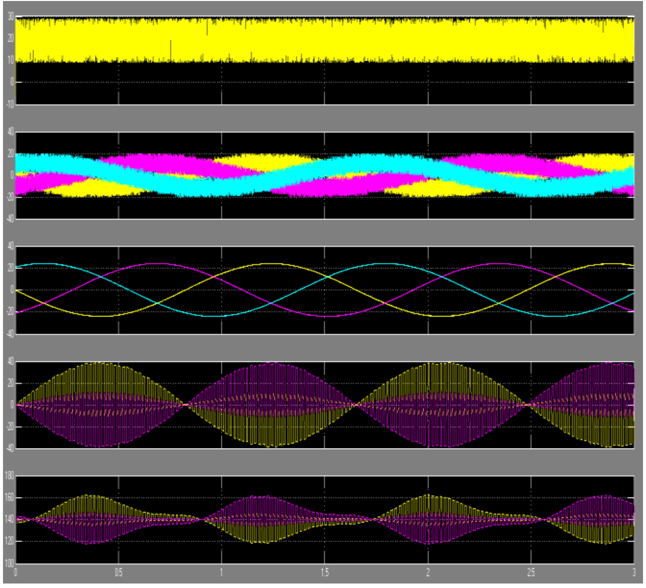

Fig. 9. Experimental steady-state waveforms when I1∗ = 17 A (5 3 %), f ∗ = 1 Hz, and TL = 60%, where I0 = 12.0 A (65%).

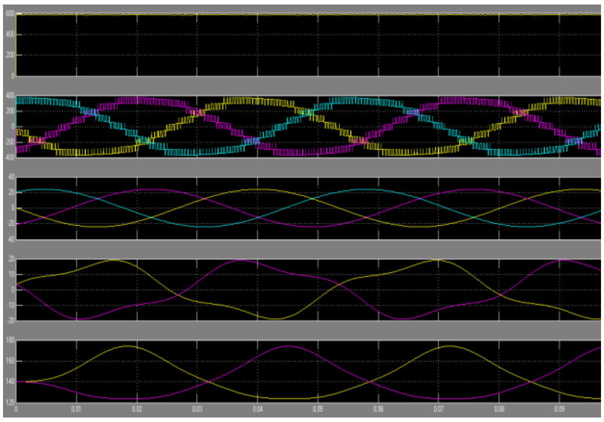

Fig. 10. Experimental steady-state waveforms when I1∗ = 17 A (53%), f ∗ = 15 Hz, and TL = 60%, where I0 = 12.0 A (65%).

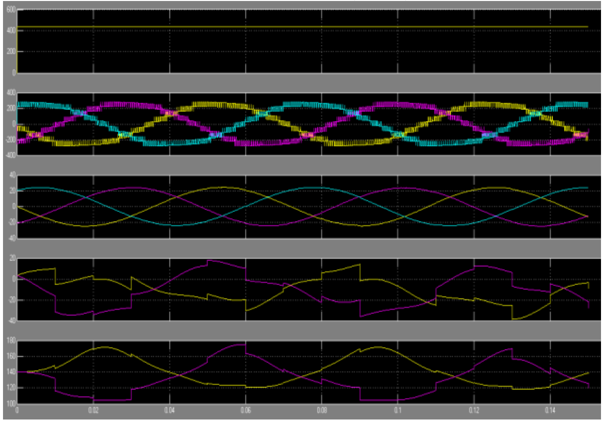

Fig. 11. Experimental steady-state waveforms with I1∗ = 17 A (53%), f ∗ = 20 Hz, and TL = 60%, where I0 = 12.0 A (65%).

VI. CONCLUSION

This paper has proposed a practical start-up method for a DSCC-driven induction motor with no speed sensor from standstill to middle speed. This start-up method is characterized by combining capacitor-voltage control and motor-speed control. The motor-speed control with the minimal stator current under a load torque is based on the combination of feedback control of the three-phase stator currents with feed forward control of their amplitude and frequency. The arm-current amplitudes and ac-voltage fluctuations across each of the dc capacitors can be reduced to acceptable levels. An experimental result obtained from a 400-V 15-kW downscaled system has shown that the motor loaded with 60% can achieve a stable start up from standstill to a middle speed of Nrm = 588 min−1 without overvoltage and over current. The start-up torque has been increasing by a factor of three, without additional stress on both arm currents and ac-voltage fluctuations. This method is suitable particularly for adjustable-speed motor drives of large-capacity fans, blowers, and compressors for energy savings.

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