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A Systematic Motor Drive with Autonomous Power Control Based on Cascading Multilevel Inverters Using SPWM

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Abstract:

This paper presents a cascaded-multilevel-inverter-based motor drive system with integrating energy source and segmented energy storage. . Recently, cascaded multilevel inverters with single energy source and multiple capacitors as energy storage for motor drive applications. In particular, it can achieve an effective real power distribution between the energy source, the energy storage, and the electric motor by an autonomous power regenerative control system. .

An autonomous power regenerative control system including voltage balancing control of segmented energy storage is developed to reduce the adverse effect of power transients on energy sources, recover the regenerative power from the motor, and improve the system dynamic performance and power quality, perform the smooth power transition between different operation modes and provide accurate speed tracking . A 5.5-kW permanent-magnet synchronous motor (PMSM) drive system has been built in the laboratory. Simulation results are provided to demonstrate the effectiveness of the proposed motor drive system.

Index Terms:

Operation mode analysis, Autonomous power regenerative control, cascaded multilevel inverter, electric motor, energy storage, objective capacitor voltage control,series individual capacitor voltage balancing control,parallel cluster capacitor voltage balancing control.

I.INTRODUCTION:

One more alternative for a multilevel inverter is the cascaded multilevel inverter or series H-bridge inverter. The series H-bridge inverter appeared in 1975. Cascaded multilevel inverter was not fully realized until two researchers, Lai and Peng. They patented it and presented its various advantages in 1997. Since then, the CMI has been utilized in a wide range of applications. With its modularity and flexibility, the CMI shows superiority in high-power applications, especially shunt and series connected FACTS controllers. The CMI synthesizes its output nearly sinusoidal voltage waveforms by combining many isolated voltage levels. By adding more H-bridge converters, the amount of Var can simply increased without redesign the power stage, and build-in redundancy against individual H-bridge converter failure can be realized.

A three-phase CMI topology is essentially composed of three identical phase legs of the series-chain of Hbridge converters, which can possibly generate different output voltage waveforms and offers the potential for AC system phase-balancing. This feature is impossible in other VSC topologies utilizing a common DC link. Since this topology consists of series power conversion cells, the voltage and power level may be easily scaled. The dc link supply for each full bridge converter is provided separately, and this is typically achieved using diode rectifiers fed from isolated secondary windings of a three-phase transformer. Phase-shifted transformers can supply the cells in medium-voltage systems in order to provide high power quality at the utility connection.

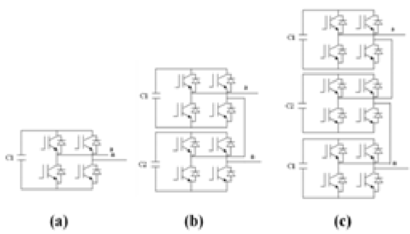

Fig 1: Single phase structures of Cascaded inverter (a) 3-level, (b)5-level, (c) 7-level

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Operation of CMLI:

The converter topology is based on the series connection of single-phase inverters with separate dc sources. It shows the power circuit for one phase leg of a three-level , fivelevel and seven-level cascaded inverter. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. In a 3-level cascaded inverter each single-phase full-bridge inverter generates three voltages at the output: +Vdc, 0, -Vdc (zero, positive dc voltage, and negative dc voltage). This is made possible by connecting the capacitors sequentially to the ac side via the power switches. The resulting output ac voltage swings from -Vdc to +Vdc with three levels, -2Vdc to +2Vdc with five-level and -3Vdc to +3Vdc with seven-level inverter. The staircase waveform is nearly sinusoidal, even without filtering. For a three-phase system, the output voltage of the three cascaded converters can be connected in either wye (Y) or delta (Δ) configurations. For example, a wye-configured 7-level converter using a CMC with separated capacitors is illustrated.

This paper proposes a cascaded-multilevel-inverter-based motor drive system integrating energy sources and segmented energy storage. In particular. Accordingly, the proposed energy storage-voltage balancing method will enable energy storage to provide not only harmonic compensation during steady state but also real power compensation during the acceleration and deceleration modes of a motor it can achieve an effective real power distribution between the energy source, the energy storage, and the electric motor by an autonomous power regenerative control system. An autonomous power regenerative control system including voltage balancing control of segmented energy storage is developed to perform the smooth power transition between different operation modes and provide accurate speed tracking.

II. SYSTEM DESCRIPTION OF PROPOSED CASCADED MULTILEVEL INVERTER WITH SEGMENTED ENERGY STORAGE.:

A.System Description:

The proposed cascaded-multilevel-inverter-based motor drive system with segmented energy storage is shown in Fig. 2.

The cascaded multilevel-inverter cells include n auxiliary inverters and one main inverter for each phase. The number of auxiliary-inverter cells of each phase can be selected by considering the tradeoff among the cost, the power loss, the power quality, and the power compensation capability. The three-level H-bridge inverter cells connected to the energy source and the energy storage are defined as the "main" inverter and the "auxiliary" inverters, respectively .For example, a large number of cells may help improve power quality and provide enough power compensation capability. However, it also leads to an extra device count, a complicated control system, and an increased cost.

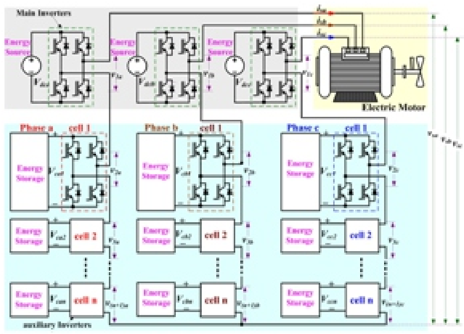

Fig.2. Proposed cascaded-multilevel-inverter-based motor drive with segmented energy storage.

In this paper, the configuration is applied to a downscaled 5.5-kW PMSM drive system, which has been built in the laboratory to verify the proposed ideas experimentally. The dc voltage of the main inverter was selected to be 150 V, and the dc voltage of each auxiliary inverter is varied between 37.5–75 V. the dc voltage of each main-inverter module and of auxiliary-inverter modules are unsymmetrical, and the dc voltage of the auxiliary inverter is lower than that of the main inverter. The main inverter switches at fundamental frequency, and the auxiliary inverters operate at a higher switching frequency. The total output voltage of each phase is therefore synthesized by a quasi-square wave for the main inverter and pulsewidth-modulation (PWM) waveforms for the auxiliary inverters using hybrid modulation with phase-shift control.This technology can be used in the next-generation electric ship to improve the efficiency, the dynamic performance, and the power quality of high-power motor drives. In addition, it is also beneficial for heavy-duty electric vehicles with large electric-drive train. The voltage ratio between the main inverter and the total sum of auxiliary inverters of each phase in Fig. 1 is defined as

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$k = (V_{dci}/\sum_{j=1}^{n} V_{cij})\ (i = a, b, c)$.

The voltage ratio is selected based on the consideration to achieve the best power quality by maximizing the number of synthesized voltage levels. Another consideration for the voltage ratio selection is to minimize the circulating energy among the cascaded inverters and to increase the efficiency of the overall system. In this paper, k is selected as 1:1 at the beginning of one driving cycle, and the maximum value of k is set to be 2:1 at the end of acceleration mode. The value of k is required to change during acceleration and deceleration modes, so that the energy storage can provide or absorb power.

B.Energy Storage Design:

The energy storage is a very important system component since it affects the dynamic performance of the electric motor and the energy source. In this paper, a UC is selected as the energy storage due to its high-power density leading to good dynamic performance. It is shown that the UC should be able to transfer sufficient energy to meet the requirements of the electric motor during power transitions. As a result, the proper design of the energy storage is essential. After the power-distribution strategy is designed, the energy storage size can be accordingly designed. The maximum energy required by the electric motor is determined by the maximum power and the desired response time during power transition. Consequently, Wmax can be derived as in

$$W_{\max} = \frac{1}{2} P_{\max} t_c$$

Where $P_{\max} = T_{e,\max}\omega_{m,\max}$. $\omega_{m,\max}$ is the maximum rotor mechanical speed, $T_{e,\max}$ is the maximum of the electric torque, and t_c is the desired speed response time during power transition, as shown in Fig. 2(a)

The energy capacity of a UC is affected by its capacitance and voltage variation range. Accordingly, the maximum energy delivered by the UC can be derived as

$$W_{\max} = \frac{3n}{2} C_{UC} \left(V_{C,\max}^2 - V_{C,\min}^2\right)$$

Where C_{UC} is the capacitance of each UC, $V_{C,\max}$ is the maximum voltage of the UC, $V_{C,\min}$ is the minimum voltage of the UC, and n is the number of cascaded-auxiliary-inverter cells of each phase.

Therefore, the total capacitance of the UC can be calculated as

$$C_{UC} = \frac{P_{\max} t_c}{3n\left(V_{C,\max}^2 - V_{C,\min}^2\right)}.$$

III AUTONOMOUS POWER REGENERATIVE CONTROL SYSTEM INCLUDING THE POWER FLOW CONTROL, AND THE ENERGY-STORAGE-VOLTAGE BALANCING CONTROL:

A control system has been also developed, as shown in Fig. 3, to achieve the proposed power-distribution strategy. It includes three control subsystems, i.e., a PMSM vector control, a power flow control, and an energy-storage-voltage balancing control. The objective of the energy-storage-voltage balancing control is to generate the adjustments of the auxiliary-inverter outputs Δv_{2i} and Δv_{3i}, which determines the power compensation performance of the energy storage during acceleration and deceleration transitions. The desired stator voltage reference $v_{Si}^{*}\ (i = a, b, c)$ is first generated from the PMSM vector control block, which has been intensively researched and will not be repeated in this paper. In the proposed control system, the voltage distribution of v_{Si}^{*} between the main inverter and the auxiliary inverters dominates power distribution between the energy source, the energy storage, and the electric motor.

Finally, the desired stator voltage v_{si} is synthesized by the output voltages of main inverters and auxiliary inverters. In this control system, P_{Source} and P_{Motor} are directly controlled to follow the desired reference, so that P_{Storage} can be autonomously regulated to charge/discharge the energy storage. Therefore, this type of controller can be called an autonomous power regenerative control system.

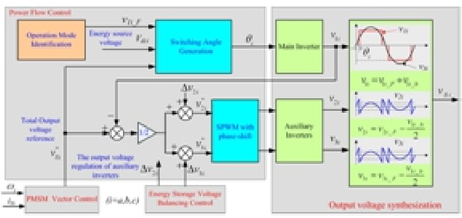

Fig. 3.Proposed power flow control system.

A.Power Flow Control And Output-Voltage Synthesization:

In Fig.3, the "operation-mode identification" module is designed to identify the operation modes of one driving

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cycle and to generate the corresponding V_{1i_F}. Voltages V_{dci}, v^*_{Si}, and V_{1i_F} are then provided to "switching-angle generation" module to generate the switching angle θ_i based on (7). After obtaining θ_i, the main inverter outputs the quasi-square-wave voltage v_{1i}. In addition, to get the desired output voltages of auxiliary inverters v_{2i} and v_{3i}, the corresponding references v^*_{2i} and v^*_{3i} are sent to the "SPWM with phase shift" module. v^*_{2i} and v^*_{3i} are derived by combining $(v^*_{Si} - v_{1i})/2$ with their respective voltage compensation components Δv_{2i} and Δv_{3i} from the energy-storage-voltage balancing control mechanism.

The output-voltage synthesization is shown in Fig. 3 for the selected application of this paper, where n = 2. It can be extended to any n number. The main-inverter output voltage is defined as v_{1i} $(i = a, b, c)$. The auxiliary-inverter output voltages are defined as v_{2i} and v_{3i}, respectively. v_{1i} is fabricated by controlling the main inverter switching at fundamental frequency. Hence, the fundamental switching angle θ_i of the main inverter will decide P_{Source} to follow the desired power trajectory. In order to find θ_i, P_{Source} is first expressed as follows, where V_{1i_F} is the magnitude of the fundamental component of v_{1i}, and i_{sq} is the q-axis stator current in the synchronous reference d − q frame rotating at the rotor electrical speed ω_r:

$$P_{Source} = \frac{3}{2} V_{1i\_F} i_{sq}, \quad i = a, b, c.$$

According to a simplified driving cycle shown in Fig. 5, P_{Source} can be calculated as

$$P_{Source} = \begin{cases} P_1 = \frac{2}{p}(T_{e1}\omega_1), & 0 \le t \le t_1 \\ P_2 = \frac{2}{p}(T_{e2}\omega_2), & t_2 \le t \le t_3 \\ P_3 = \frac{2}{p}(T_{e3}\omega_3), & t_4 \le t \\ P_1 + \frac{t-t_1}{t_2-t_1}(P_2 - P_1), & t_1 \le t \le t_2 \\ P_2 - \frac{t-t_3}{t_4-t_3}(P_3 - P_2), & t_3 \le t \le t_4 \end{cases}$$

Where p is number of poles; $T_{e1} = k_t i_{sq1}$; $T_{e2} = k_t i_{sq2}$; $T_{e3} = k_t i_{sq3}$; k_t is the torque constant; and i_{sq1}, i_{sq2}, and i_{sq3} are i_{sq} values at ω_1, ω_2 and ω_3, respectively.

Where V_{dci} is the dc voltage of the main inverter of each phase, V_{1i_F} is the fundamental component of v_{1i}, and v_{1i_h} is the harmonic component of v_{1i}. Angle θ_i can be derived from the fundamental component of v_{1i} and can be written as

$$\theta_i = \cos^{-1}\left(\frac{\pi}{4} \times \frac{V_{1i\_F}}{V_{dci}}\right), \quad i = a, b, c.$$

B.Energy-Storage-Voltage Balancing Control :

The detailed energy-storage-voltage balancing control is shown in Fig. 7, which includes three cascaded control blocks.Objective-capacitor voltage control.Parallel cluster-capacitor voltage balancing control.Series individual-capacitor voltage balancing control.

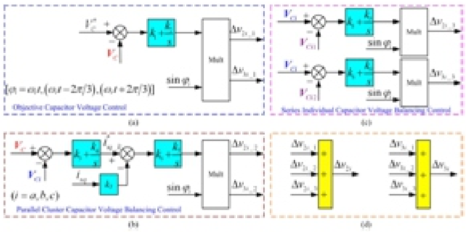

Fig. 4. Energy storage voltage balancing control: (a) Objective-capacitor voltage control; (b) parallel cluster-capacitor voltage balancing control; (c) series individual-capacitor voltage balancing control; and (d) the synthesized adjustments of six auxiliary inverters. In the proposed controller, the objective-capacitor voltage control can be considered as an inner loop with a response speed faster than the other two controllers. The parallel cluster-capacitor voltage balancing control operates as the middle loop with faster response speed than the series individual-capacitor voltage balancing control being regarded as the outer loop. This type of triple loop control structure can achieve fast voltage regulation, high steady-state accuracy, and high dynamic performance.

1) Objective-Capacitor Voltage Control:

Fig. 4(a) shows the objective-capacitor voltage control. Where V_{Ci} $(i = a, b, c)$ is the average voltage of the two capacitors in each phase. V_{Ci} Can be calculated as follows, where V_{Ci1} and V_{Ci2} are the individual capacitor voltages in each phase.

$$V_C = \frac{1}{3}(V_{Ca} + V_{Cb} + V_{Cc})$$

$$V_{Ci} = \frac{1}{2}(V_{Ci1} + V_{Ci2}), \quad i = a, b, c.$$

The output of the PI controller multiplied by $\sin\varphi_i$ fabricates the first adjustments Δv_{2i-1} and Δv_{3i-1}, which are used to regulate the output voltages of the two auxiliary inverters in each phase.

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2)Parallel Cluster-Capacitor Voltage Balancing Control:

This balancing control is shown in Fig. 4(b), which can keep V_{Ci} equal to V_C. The outer voltage loop generates the current command $i^*_{sq\_k}$ related to synchronous q-axis current by a PI controller. The inner current loop controls current $k_5 i_{sq}$ to track this command, where k_5 is the current gain. The second adjustments Δv_{2i-2} and Δv_{3i-2} of the output voltages of two auxiliary inverters in each phase can be generated by multiplying the inner loop output with $\sin\varphi_i$.

3) Series Individual-Capacitor Voltage Balancing Control:

Fig. 4(c) shows the series individual-capacitor voltage balancing control. Voltages V_{Ci1} and V_{Ci2} are individually controlled to be V_{Ci} by two PI controllers in each phase. The outputs of PI controllers multiplied by $\sin\varphi_i$ is also used to regulate the output voltages of two auxiliary inverters in each phase as the third adjustments Δv_{2i-3} and Δv_{3i-3}, respectively.

All these three adjustments are synthesized as the auxiliary inverter output-voltage regulation Δv_{2i} and Δv_{3i} in each phase, which can balance the capacitor voltages, as shown in Fig. 4(d).

IV.Proposed Power distribution strategy:

The proposed power-distribution strategy during a typical driving cycle is presented in Fig. 2. The power flow to/from the electric motor, the energy sources, and the energy storage is defined as P_{Motor}, P_{Source} and P_{Storage}, respectively. Where

$$P_{\text{Source}} + P_{\text{Storage}} = P_{\text{Motor}}$$

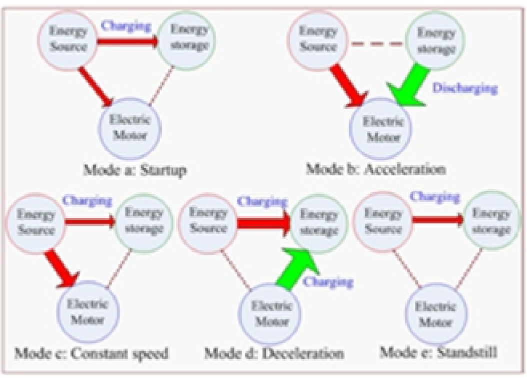

Fig.5. Power flow between the energy source, the energy storage, and the electric motor in different operation modes.

The corresponding power flow between the energy source, the energy storage, and the electric motor is described in Fig. 5. During the startup mode, the energy source charges the energy storage to the desired value. The energy source also provides a small value of power to the electric motor so that it can start at a low speed. The dotted line between the energy storage and the electric motor means that there is no power exchange between them.

During the acceleration mode, both the energy source and the energy storage provide power to the electric motor. However, the energy source provides power with a linearly increasing slope.and the energy storage supplies peak power to achieve fast acceleration if required. The energy storage voltage will decrease during this interval due to the discharging. During a constant-speed period, the energy source provides all the power required by the electric motor, and the energy storage receives a small amount of power from the energy source to maintain the voltage at the end of the accelerating mode.

During the deceleration mode, the energy storage recovers all the regenerative energy from the electric motor so that the energy storage voltage will increase. The stored energy can be released during the next acceleration mode. In order to eliminate hard power/current stress on an energy source such as a battery and maintain a smooth voltage transient of energy source between two modes, PSource is controlled to decrease with a finite slope until a standstill situation is reached. During the standstill mode, the energy source can provide the small power needed to maintain the energy storage voltage.

The stored energy can be released during the next acceleration mode. In order to eliminate hard power/current stress on an energy source such as a battery and maintain a smooth voltage transient of energy source between two modes, PSource is controlled to decrease with a finite slope until a standstill situation is reached. During the standstill mode, the energy source can provide the small power needed to maintain the energy storage voltage.

IV .SIMULATION DESTGN OF PROPOSED CASCADED MULTI LEVEL INVERTER:

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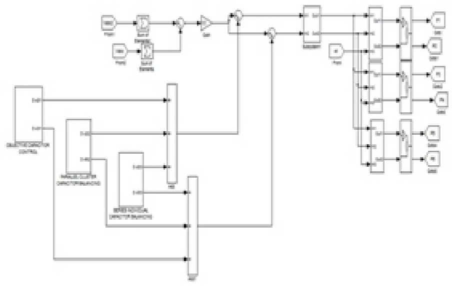
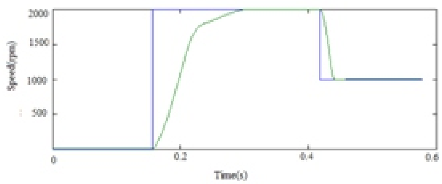


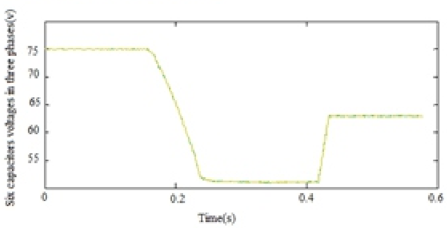
V. SIMULATION RESULTS:

Figs.shows simulation results over a typical driving cycle including acceleration, deceleration, and constant-speed modes. The constant load torque of 10 N • m is used in this driving cycle.



(a) speed

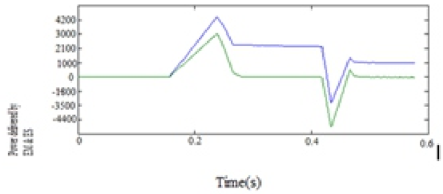
Fig. (a) shows the speed dynamic response when the speed command N_e^* changes from 0 to 2000 r/min at 0.1 s and then back to 1000 r/min at 0.4 s. The actual speed N_e follows N_e^* fast and smoothly.



(b) Six capacitors output voltages:

Fig. (b) shows the corresponding six capacitor voltages. The capacitor voltage is 75 V before the starting acceleration mode. During the acceleration period, the capacitors are discharged to provide required peak power; thus, the voltages decrease from 75 to 51.5 V.

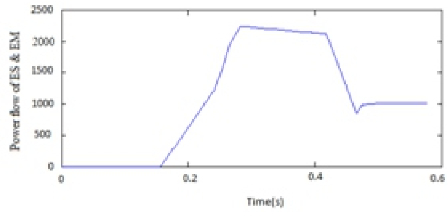
The capacitors then receive a small power from dc sources to keep 51.5 V at a constant-speed period. During deceleration period, the capacitors recover regenerative energy from PMSM; thus, the capacitor voltages increase from 51.5 to 62.5 V.



(c) Power delivered byEM& ES:

Fig (c) PMotor requires 4200-W peak power during the acceleration mode where up to 3000Wis provided by capacitors and the rest of the power is from dc sources. The capacitors continuously provide power to the PMSM in about 0.12 s until the speed reaches 2000 r/min.

Fig (d) shows Although the regenerative peak power of the PMSM is 1800W, the capacitors absorb up to 3500 W.



(d) Power flow of ES & EM Fig: 6 Simulation results of proposed motor drive: (a) Speed response; (b) six capacitor voltages of three phases; and (c) PMotor, PStorage, and (d) PSource.

The simulated waveforms of P_{Motor}, $P_{Storage}$, and P_{Source} are presented in (c) and (d), respectively. P_{Motor} requires 4200-W peak power during the acceleration mode where up to 3000 W is provided by capacitors and the rest of the power is from dc sources. The capacitors continuously provide power to the PMSM in about 0.12 s until the speed reaches 2000 r/min. Although the regenerative peak power of the PMSM is 1800 W, the capacitors absorb up to 3500 W.

This is because the power from dc sources is linearly decreasing during the deceleration period; therefore, the capacitors absorb not only regenerative power from the PMSM but also power from the dc source. the capacitors continuously absorb power from the PMSM and dc sources in about 0.04 s until the speed reaches to 1000 r/min.

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V CONCLUSION:

This paper has proposed a cascaded-multilevel-inverterbased motor drive system with segmented energy storage elements. A power-distribution strategy between the energy source, the energy storage, and the electric motor has been developed and implemented by a proposed autonomous power regenerative control system to perform smooth power transition between different operation modes and provide accurate speed tracking.In the proposed motor drive system, the energy storage has been designed not only to provide harmonic compensation but also to be capable of recovering regenerative energy during the deceleration mode and reapplying this energy during acceleration transients which improves the efficiency &powerquality.

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