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Integrated Energy Storage NPC Inverter based Motor-drive with Autonomous Power Control



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Abstract:

This paper presents a NPC-multilevel-inverterbasedmotor drive system with integrated segmented energy storage.A power-distribution strategy among the energy source, the-segmented energy storage, and the electric motor is proposed underdifferent operation modes. A design guideline for energy storageis provided to meet the proposed power-distribution strategy.Moreover, the energy storage features not only implementing theharmonic compensation in all operating modes but also providingpeak power during acceleration and absorbing regenerative powerduring deceleration, which improves the energy efficiency of the motor drive system and reduces the size of the energy source. Anautonomous power regenerative control system including voltagebalancing control of segmented energy storage is developed toperform the smooth power transition between different operationmodes and provide accurate speed tracking. A 5.5-kW permanent-magnet synchronous motor (PMSM) drive system has been simulated. Simulation results are provided to demonstrate the effectiveness of the proposed motorsystem.

Index Terms:
Autonomous power regenerative control, NPC multilevel inverter, electric motor, energy storage, voltagebalancing control.

I. INTRODUCTION:

IT IS WELL known that energy storage devices are beneficialin a motor drive system to improve system dynamicperformance and efficiency since they can recover the regeneratedenergy and provide peak power during transients [1]–[7]. Power-electronic technology provides a favorable approach to achieve power management between energy sources and energy storage in motor drive system. Refs. introducea typical motor drive system configuration where bidirectionaldc–dc converters are used to interface energy source and energystorage. This type ofsystemconfiguration can achieve flexible power management strategy between the energy source,the energy storage, and the motor, as well as reduce theadverse effects of energy-storage-voltage variation on systemperformance. However, it requires two-stage energy conversion,i.e., a dc–dc and a dc–ac stage, between the energy source,the energy storage, and the motor. Furthermore, the dc–dc converter suffers considerable switching and conduction loss with a high-power application, which results in lower efficiency.It also increases the cost and system complexity and posesstability issues, particularly under high inrush currents [8]–[10].Z-source networks have been considered to replace these dc–dcconverters [10]. However, the loss in the exclusive Z-sourcenetwork cannot be particularly ignored for a high boost ratiowith low dc voltage input and high ac voltage output.

NPC multilevel inverters are popular in high-power applications such as static synchronous compensation (STATCOM), hybrid renewable energy system, and motor drive system [11]–[18]. The motor drive system with NPC multilevel-inverter-interfacing energy sources has been found to achieve desirable merits for high-power applications, as wellas heavy-duty electric and hybrid electric vehicles [11], [19],[20]. The modular structure is helpful to the cost reduction due to enabling low-cost-semiconductor application, low manufacturing cost, etc. Moreover, the NPC multilevelinverter features low electromagnetic interference, exceptional power qualities at low frequency,transformerless topology,and enhanced fault tolerance capability, etc. [20]. High energy efficiency with this configuration can be also derived due to the single-stage energy conversion between energy sourcesand motor. It can also facilitate interfacing segmented energysource or energy storage in order to scale up to high voltageand high power with the modular structure. Recently, NPC multilevel inverters with single energy source and multiplecapacitors as energy storage for motor drive applications havebeen reported [13]–[15], but capacitors in this research wereonly applied to provide harmonic cancellation. The distributionof real power between the energy source and the energy storagewas not achieved, which limits the energy storage's functions. This paper proposes a NPC -multilevel-inverter-based motor drive system integrating energy sources and segmentedenergy storage. In particular, it can achieve an effective realpower distribution between the energy source, the energy storage,and the electric motor by an autonomous power regenerativecontrol system, which will reduce the adverse effect ofpower transients on energy sources, recover the regenerativepower from the motor, and improve the system dynamic performanceand power quality. Moreover, a new energy-storagevoltagebalancing method is presented in this paper, whichis different from those in [17], [19], and [21]. Although itis also achieved by the active control, the voltage referencegeneration and the control-enabling mechanism are determinedby different operation modes. Therefore, the voltage compensation components used for voltage balancing is differentin the proposed method.

Accordingly, the proposed energystorage-voltage balancing method will enable energy storage toprovide not only harmonic compensation during steady statebut also real power compensation during the acceleration and deceleration modes of a motor. This paper is outlined as follows. After the introductionsection, an insightful illustration of the proposed powerdistributionstrategy between the energy source, the energystorage, and the electric motor during five operation modes isdescribed in Section II. The design of the energy storage is alsodeveloped in this section to meet the torque and speed requirementsof an electric motor. Section III presents the autonomouspower regenerative control system including the motor vectorcontrol, the power flow control, and the energy-storagevoltagebalancing control. In Section IV, the proposed system is firstsimulated in a MATLAB/Simulink simulation platformand then implemented on a 5.5-kW permanentmagnetsynchronous motor (PMSM) drive test bed. Simulation results are presented to verify the effectivenessof the proposed motor drive system. Finally, conclusions are presented in Section V.

II. SYSTEM DESCRIPTION AND POWER DISTRIBUTION STRATEGY

A. System Description:

The proposed NPC -multilevel-inverter-based motor drive system with segmented energy storage is shown in Fig. 1.The level NPC inverter cells connected to the energysource and the energy storage are defined as the "main" inverterand the "auxiliary" inverters, respectively. The NPC multilevel-inverter cells include n auxiliary inverters and onemain inverter for each phase. The number of auxiliary-invertercells of each phase can be selected by considering the tradeoffamong the cost, the power loss, the power quality, and the powercompensation capability. For example, a large number of cellsmay help improve power quality and provide enough powercompensation capability. However, it also leads to an extradevice count, a complicated control system, and an increasedcost. In this configuration, the dc voltage of each maininverter module and of auxiliary-inverter modules are unsymmetrical,and the dc voltage of the auxiliary inverter is lower than thatof the main inverter. The main inverter switches at fundamentalfrequency, and the auxiliary inverters operate at a higherswitching frequency. The total output voltage of each phaseis therefore synthesized by a quasi-square wave for the maininverter and pulsewidthmodulation (PWM) waveforms for theauxiliary inverters using hybrid modulation with phase-shiftcontrol.

The phase-shift PWM control for auxiliary inverterswith low-voltage switching devices can achieve an equivalent carrier frequency with 2n times as the reference PWM carrierfrequency, which can maintain a good power quality withreduced switching loss. The dc voltages of all auxiliary invertersare controlled to be symmetrical; otherwise, the inverteroutput voltage will be generated with an asymmetrical adjacentvoltage step, which may lead to the undesired harmonicvoltage.The voltage ratio between the main inverter and the total sum of auxiliary inverters of each phase in Fig. 1 is defined as k = (Vdci/_nj=1 Vcij) (i = a, b, c). Unlike thetraditional NPC multilevel inverters, the value of k is required to change during acceleration and deceleration modes, so that theenergy storage can provide or absorb power. In this paper, k isselected as 1:1 at the beginning of one driving cycle, and themaximum value of k is set to be 2:1 at the end of accelerationmode. The voltage ratio is selected based on the considerationto achieve the best power quality by maximizing the numberof synthesized voltage levels.

Another consideration for thevoltage ratio selection is to minimize the circulating energyamong the cascaded inverters and to increase the efficiency ofthe overall system [12], [22], [23]. Finally, in order to allowthe output-voltage harmonics generated around the frequencymultiples of the 2n switching frequency of auxiliary inverters,output voltage should be synthesized with the same adjacent voltage step [23]. The proposed technology can be used in the next generationelectric 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 since the isolated energy source can be implemented by individual battery packs and isolatedenergy storage can be achieved by segmented ultracapacitors(UCs). The segmented energy storage employing in the systemcan greatly reduce the size of the battery and allow the usageof a lower voltage battery, resulting in lower cost on the batteryside.

The cascaded structure also provides the benefit of usinglower voltage UC. Since a UC features much higher powerdensity and longer cycle life compared with the battery, theactive interface of the battery and the UC through a cascadedstructure will achieve advantages including extended life cycleof the battery, reduced battery loss, faster system dynamic, andbetter fuel economy. In this paper, the configuration is applied to a downscaled5.5-kW PMSM drive system, therefore, thenumber of NPC -auxiliary-inverter modules of each phasein this application was selected to be 2. The dc voltage of thmain inverter was selected to be 150 V, and the dc voltage ofeach auxiliary inverter is varied between 37.5–75 V.

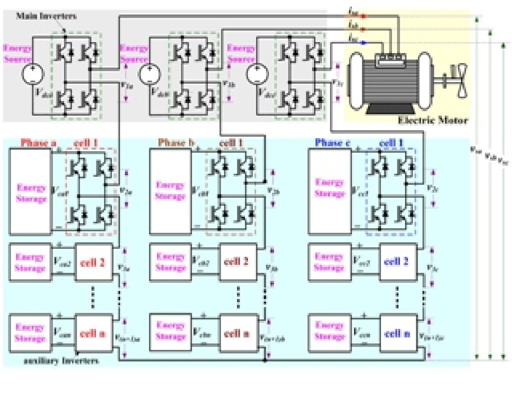

Fig. 1. Proposed NPC -multilevel-inverter-based motor drive with segmented energy storage.

B. Proposed Power Distribution Strategy and Operation-Mode Analysis:

The proposed power-distribution strategy during a typical driving cycle is presented in Fig. 2. The power flow to/ fromthe electric motor, the energy sources, and the energy storageis defined as PMotor, PSource and PStorage, respectively, wherePSource + PStorage = PMotor. In Fig. 2(a), PSource is controlledto follow the trajectory highlighted in red. This trajectory isunidirectional with a mild increase/decrease slope; thus, itcan be applied to a unidirectional energy source having slowdynamics. It is also beneficial for bidirectional energy source such as battery since the battery demonstrates poor performanceto recover the regenerative energy, as well as slower dynamics when compared with the UC [4]. The battery is thereforedesired to be controlled not to absorb regenerative power andnot to allow fast power change when the UC is selected as theenergy storage to work with the battery. The power trajectoryof the energy storage is shown as a green line. The energytransferred shown in the shadow region results from the powercoordination control between the energy source and the energystorage. Consequently, the energy source can be designed with significant size, cost reduction, and efficiency improvement.

For a battery-based energy source, the reduced power stressduring transients can lead to reduced battery loss and longerlifetime. Moreover, the energy storage is designed to receivepower from the energy source to achieve startup without anyadditional charger, which reduces the system cost further.The corresponding power flow between the energy source,the energy storage, and the electric motor is described inFig. 2(b). During the startup mode, the energy source chargesthe energy storage to the desired value. The energy source alsoprovides a small value of power to the electric motor so that itcan start at a low speed. The dotted line between the energystorage and the electric motor means that there is no powerexchange between them. During the acceleration mode, boththe energy source and the energy storage provide power tothe electric motor. However, the energy source provides powerwith a linearly increasing slope, as shown in Fig. 2(a), and the energy storage supplies peak power to achieve fast accelerationif required. The energy storage voltage will decrease duringthis interval due to the discharging. During a constant-speedperiod, the energy source provides all the power required bythe electric motor, and the energy storage receives a smallamount of power from the energy

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source to maintain the voltageat the end of the accelerating mode. During the decelerationmode, the energy storage recovers all the regenerative energyfrom the electric motor so that the energy storage voltage willincrease. The stored energy can be released during the nextacceleration mode. In order to eliminate hard power/currentstress on an energy source such as a battery and maintain asmooth voltage transient of energy source between two modes,

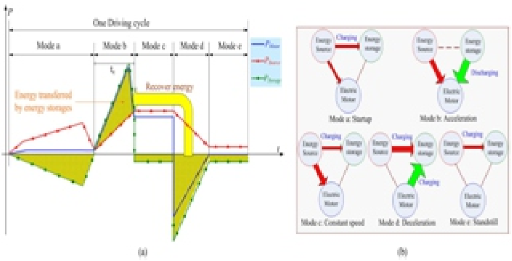

Fig. 2. Proposed power-distribution strategy: (a) Power trajectory of energy source, energy storage, and electric motor during one driving cycle; and (b) powerflow between the energy source, the energy storage, and the electric motor in different operation

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.

C. 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. 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.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 in Fig. 2(a) that the UC should be able to transfer sufficient energy to meet the requirements of the electric motor during power transitions. Therefore, the maximum energy transfer between the UC and the electric motor will determine the size of the UC. 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

$$W_{\max} = \frac{3n}{2} C_{\mathrm{UC}} \left(V_{C,\max}^2 - V_{C,\min}^2\right) \quad (1)$$

where CUC is the capacitance of each UC, VC,max is the maximum voltage of the UC, VC,min is the minimum voltage of the UC, and n is the number of cascaded-auxiliary-inverter cells of each phase. 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

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

where P_{max} = Te,maxωm,max, ωm,max is the maximum rotor mechanical speed, Te,max is the maximum of the electric torque, and tc is the desired speed response time during power transition, as shown in Fig. 2(a). Therefore, the total capacitance of the UC can be calculated as

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

In the application selected in this paper, the proper capacitanceis obtained based on the following parameters: Pmax =5.5 kW, Vc,max = 75 V, Vc,min = 37.5 V, n = 2, and tc =0.1 s. Therefore, an electrolytic capacitor of 20 mF is sufficientinstead of a UC to verify the proposed power-distributionstrategy.

III. AUTONOMOUS POWER REGENERATIVE CONTROL SYSTEM:

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 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 because of the same stator current through the cascaded inverters.

The power flow control will achieve the aforementioned voltage distribution. The objective of the energy-storage-voltage balancing control is to generate the adjustments of the auxiliary-inverter outputs Δv2i and Δv3i, which determines the power compensation performance of the energy storage during acceleration and deceleration transitions.

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Finally, the desired stator voltage vsi is synthesized by the output voltages of main inverters and auxiliary inverters. In this control system, PSource and PMotor are directly controlled to follow the desired reference, so that PStorage can be autonomously regulated to charge/discharge the energy storage. Therefore, this type of controller can be called an autonomous power regenerative control system.

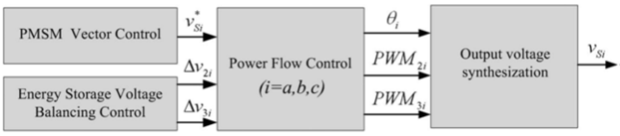

Fig. 3. Autonomous power regenerative control system

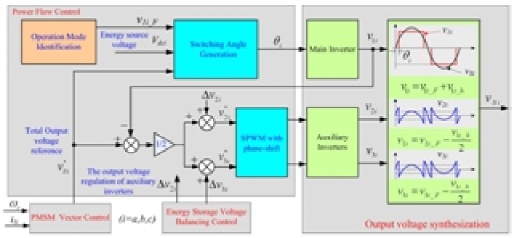

Fig. 4. Proposed power flow control system.

A. Power Flow Control and Output-Voltage Synthesization:

The output-voltage synthesization is shown in Fig. 4 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 v1i (i = a, b, c). The auxiliary-inverter output voltages are defined as v2i and v3i, respectively. v1i is fabricated by controlling the main inverter switching at fundamental frequency. Hence, the fundamental switching angle θi of the main inverter will decide PSource to follow the desired power trajectory. In order to find θi, PSource is first expressed as follows, where V1i_F is the magnitude of the fundamental component of v1i, and isq is the q-axis stator current in the synchronous reference d − q frame rotating at the rotor electrical speed ωr:

$$P_{\text{Source}} = \frac{3}{2} V_{1i\_F} i_{sq}, \quad i = a, b, c. \tag{4}$$

According to a simplified driving cycle shown in Fig. 5, PSource can be calculated as

$$P_{\text{Source}} = \begin{cases} P_1 = \frac{2}{p}(T_{e1}\omega_1), & 0 \le t \le t_1 \\ P_2 = \frac{2}{p}(T_{e2}\omega_2), & t_2 \le t \le t_3 \\ P_3 = \frac{2}{p}(T_{e3}\omega_3), & t_4 \le t \\ P_1 + \frac{t-t_1}{t_2-t_1}(P_2 - P_1), & t_1 \le t \le t_2 \\ P_2 - \frac{t-t_3}{t_4-t_3}(P_3 - P_2), & t_3 \le t \le t_4 \end{cases} \tag{5}$$

where p is number of poles; Te1 = ktisq1; Te2 = ktisq2; Te3 = ktisq3; kt is the torque constant; and isq1, isq2, and isq3 are isq values at ω1, ω2 and ω3, respectively.

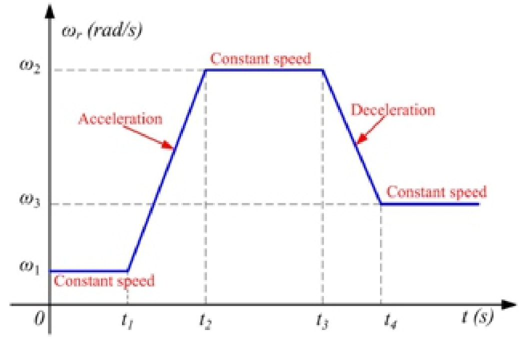

Fig. 5. Speed trajectory at one simplified driving cycle.

Therefore, V1i_F can be derived from (4). If the power loss to balance the energy storage can be negligible, V1i_F can be treated as the same as the magnitude of Vsi for a constant-speed mode. The Fourier series expansion of v1i is given by

$$\begin{cases} v_{1i} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dci}}{n\pi} \cos(n\theta_i) \sin(n\omega_r t) \\ \quad = v_{1i\_F} + v_{1i\_h} & (i = a, b, c) \\ v_{1i\_F} = \frac{4V_{dci}}{\pi} \cos(\theta_i) \sin(\omega_r t) \\ v_{1i\_h} = \sum_{n=3,5,\ldots}^{\infty} \frac{4V_{dci}}{n\pi} \cos(n\theta_i) \sin(n\omega_r t) \end{cases} \tag{6}$$

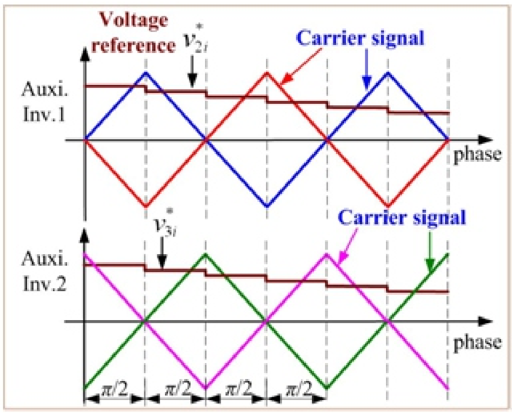

Fig. 6. PWM method with phase shift control for two auxiliary inverters in each phase.

where Vdci is the dc voltage of the main inverter of each phase,v1i_F is the fundamental component of v1i, and v1i_h is the harmonic component of v1i. Angle θi can be derived from the fundamental component of v1i and can be written as

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$$\theta_i = \cos^{-1}\left(\frac{\pi}{4} \times \frac{V_{1i\_F}}{V_{\mathrm{dci}}}\right), \quad i = a, b, c. \tag{7}$$

In Fig. 4, the “operation-mode identification” module is designed to identify the operation modes of one driving cycle and to generate the corresponding V1i_F . Voltages Vdci, v Si, and V1i_F are then provided to “switching-angle generation” module to generate the switching angle θi based on (7). After obtaining θi, the main inverter outputs the quasi-square-wave voltage v1i. In addition, to get the desired output voltages of auxiliary inverters v2i and v3i, the corresponding references v2i and v3i are sent to the “SPWM with phase shift” module.

v2i and v3i are derived by combining (vSi− v1i)/2 with theirrespective voltage compensation components Δv2i and Δv3i from the energy-storage-voltage balancing control mechanism.The operation principle of the “SPWM with phase shift”module is shown in Fig. 6. It generates the equivalent fourfold frequency as the reference PWM carrier frequency in the output terminal of two auxiliary inverters in each phase. The adjacent carrier signals have π/2 phase shift. Consequently, the auxiliary inverters output v2i and v3i, which can be expressed as

$$\begin{cases} v_{2i} = v_{2i\_F} - \frac{v_{1i\_h}}{2} \\ v_{3i} = v_{3i\_F} - \frac{v_{1i\_h}}{2} \end{cases}, \quad i = a, b, c \tag{8}$$

where v2i_F = (vsi − v1i_F /2) + Δv2i, and v3i_F = (vsi − v1i_F /2) + Δv3i are the real power components of v2i and v3i.v1i_h from the main inverter can be canceled by −v1i_h from auxiliary inverters to improve cascaded-inverter output-voltage quality. In particular, v2i_F and v3i_F determine peak powers generated or absorbed by energy storage. In this way, the proper power distribution can be achieved between the energy source,\the energy storage, and the electric motor.

B.Energy-Storage-Voltage Balancing Control:

The voltage balancing of the energy storage not only contributes to power distribution but also impacts system stability.The detailed energy-storage-voltage balancing control is shownin Fig. 7, which includes three cascaded control blocks, i.e., an objective-capacitor voltage control, a parallel cluster-capacitor voltage balancing control, and a series individual-capacitor voltage balancing control.

The objective of the control is to keep the voltage of all energy storage modules in the three phases to be the same value during all operating modes. Although the voltage of each energy storage may be directly controlled to track the desired voltage V C of only one controller, it exhibitsunsatisfactory steady and transient performance and robustness, which may affect power distribution and system stability. 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 voltagebalancing 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. 7(a) shows the objective-capacitor voltage control. The proportionalintegral (PI) controller can regulate the average voltage of six capacitors VC in three phases to the desired value V C during startup, constant-speed, and standstill modes. VC is defined in (9), where VCi (i = a, b, c) is the average voltage of the two capacitors in each phase. VCi can be calculated as follows,where VCi1 and VCi2 are the individual capacitor voltages in each phase:

$$V_C = \frac{1}{3}(V_{Ca} + V_{Cb} + V_{Cc}) \tag{9}$$

$$V_{Ci} = \frac{1}{2}(V_{Ci1} + V_{Ci2}), \quad i = a, b, c. \tag{10}$$

The output of the PI controller multiplied by sin ϕi fabricates the first adjustments Δv2i−1 and Δv3i−1, which are used to regulate the output voltages of the two auxiliary inverters ineach phase. During acceleration and deceleration transitions, this control is disabled so that the capacitor voltage can varywith the rotor speed. As a result, the capacitors will provide peak power or absorb regenerative power. In addition, the voltage at the end of acceleration and deceleration will be used as the voltage reference at a constant speed. 2) Parallel Cluster-Capacitor Voltage Balancing Control:This balancing control is shown in Fig. 7(b), which can keep VCi equal to VC. 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 k5isq to track this command, where k5 is the current gain. The second adjustments Δv2i−2 and Δv3i−2 of the output voltages of two auxiliary inverters in each phase can be

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generated by multiplying the inner loop output with sin ϕi. 3) Series Individual-Capacitor Voltage Balancing Control: Fig. 7(c) shows the series individual-capacitor voltage balancing control. Voltages VCi1 and VCi2 are individually controlled

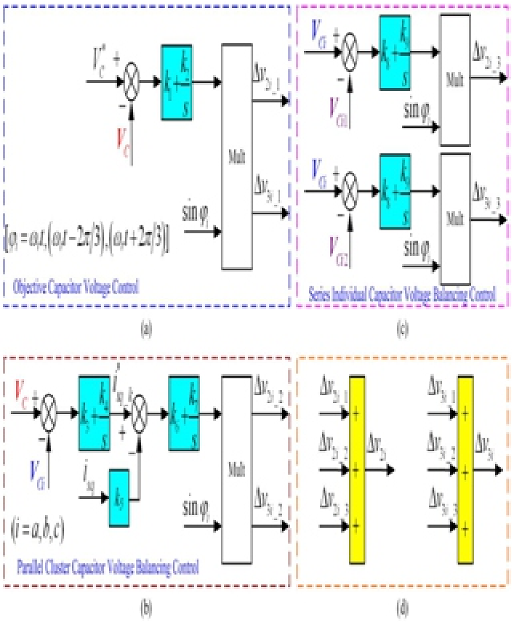

Fig. 7. Energy storage voltage balancing control: (a) Objective-capacitor voltage control; (b) parallel cluster-capacitor voltage balancing control;(c) series individual-capacitor voltage balancing control; and (d) the synthesized adjustments of six auxiliary inverters.

TABLE I
PARAMETERS OF SELECTED PMSM

Rated Power	P_{rated}	5.5 kW
Rated Voltage (Line to Line RMS value)	V_{s_rated}	230 V
Rated Current (RMS)	I_{s_rated}	23 A
Rated Torque	T_{e_rated}	26.18 N.m
Rated Speed	N_{e_rated}	2000 rpm
Number of Poles	p	8
Rotor Inertia	J	66.4e-4 Kg.m^2

to be VCi by two PI controllers in each phase. The outputs of PI controllers multiplied by sin ϕi is also used to regulate the output voltages of two auxiliary inverters in each phase as the third adjustments Δv2i−3 and Δv3i−3, respectively. The design of these PI controllers can be obtained by referring to [18]. In addition, the selection of the integrating parameters in the aforementioned PI controllers need to consider how to mitigate the effect of double frequency voltage ripple on the ac output voltage. All these three adjustments are synthesized as the auxiliary inverter output-voltage regulationΔv2i andΔv3i in each phase, which can balance the capacitor voltages, as shown in Fig. 7(d).

IV. SIMULATION RESULTS:

A small 5.5 kW PMSM drive system has been built for the purpose of Simulation verification. The key parameters of the PMSM are listed in Table I. The energy sources connected to the main inverters are three isolated rectified dc sources. There are two auxiliary inverters cascaded for each phase and each auxiliary inverter is interfaced with a 20-mF electrolytic capacitor, which is used to emulate the individual UC element in the motor drive system. The dc source voltage is selected to be 150 V, and the capacitor voltage is varied between 37.5–75 V. In order to evaluate the performance of the proposed motor drive system, simulation tests were first conducted in a combined simulation platform of MATLAB/Simulink . Figs. 8 and 9 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. Fig. 8(a) shows the speed dynamic response when the speed command Ne 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 Ne follows Ne fast and smoothly. Fig. 8(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.

Thecapacitors 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. During the complete driving cycle, the capacitor voltage balancing control is effective to keep all the six capacitors voltage balanced and symmetrical. The simulated waveforms of PMotor, PStorage, and PSource are presented in (c) and (d), respectively. 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. The relevant energy can be calculated based on Fig. 8(c). Accordingly, the range of the capacitor voltages can be derived by (3). Therefore, the power requirement from the PMSM can be met by regulating the capacitor voltage from 75 to 51.5 V, which is consistent with the results in Fig. 8(b). Although the regenerative peak power of the PMSM is 1800W, the capacitors absorb up to 3500 W.

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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.

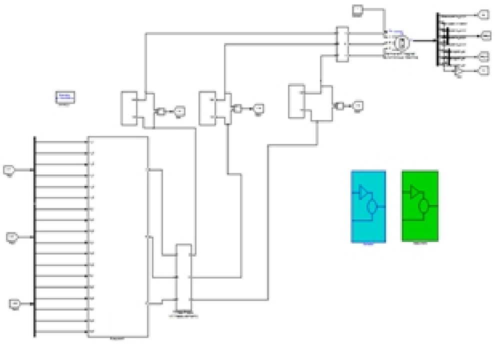


Fig 7.1: Simulation Circuit

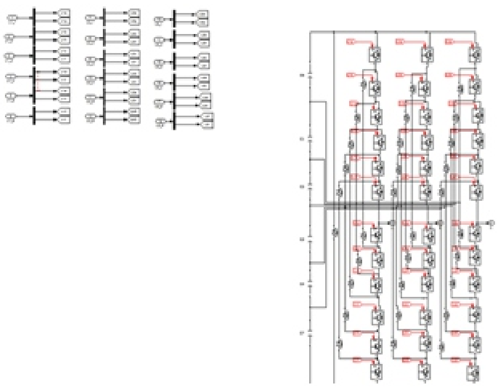


Fig 7.2: NPC Multilevel Inverter model

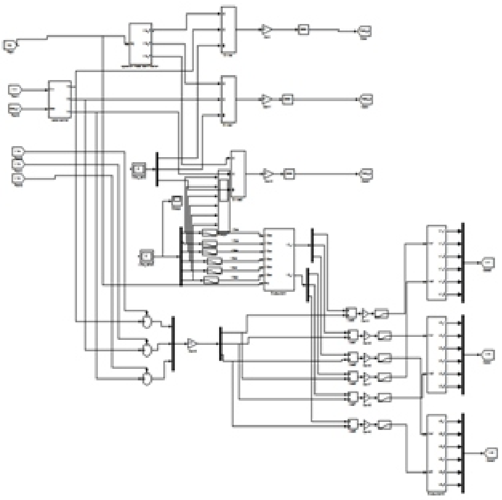
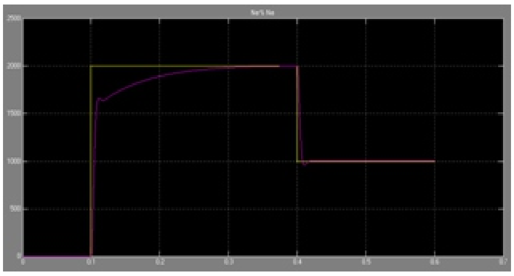
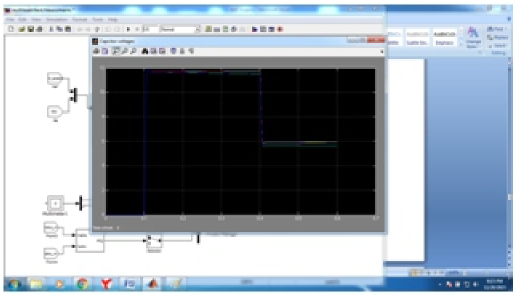


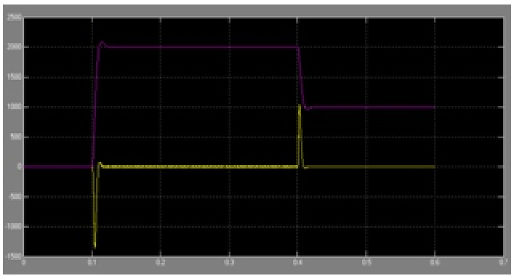
Fig 7.3: Control Strategy Model in Simulation



(a)speed response



(b) Capacitor Voltages



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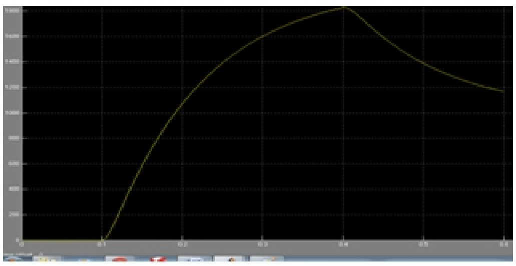

(d) Psource

Fig. 8. Simulation results of proposed motor drive: (a) Speed response; (b) six capacitor voltages of three phases; and (c) PMotor, PStorage, and (d) PSource.

is particularly beneficial for battery-based dc sources since it can reduce power stress on the battery and avoid hard voltagetransients between two modes. During the deceleration operatingmode, the capacitors continuously absorb power from the

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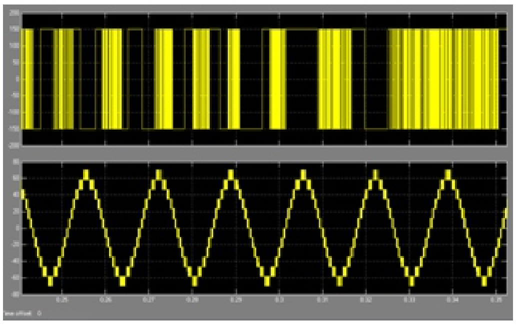

Fig. 9. Simulation results: v1a, and v3a of the a-phase during the acceleration mode.

PMSM and dc sources in about 0.04 s until the speed reaches to 1000 r/min. Accordingly, the capacitor voltage range change can be derived by (3) and by the calculated energy in Fig. 8(c).Therefore, the power requirement from the PMSM can be met by regulating the capacitor voltages from 51.5 to 62.5 V, which coincides with the results in Fig. 8(b).Fig. 9 shows the corresponding output voltages of a-phase during the acceleration period. The main inverter generates a quasi-square-wave v1a with 150-V maximum value switching at lower switching frequency synchronous with the rotor speed.The two auxiliary inverters generate PWM waveforms v2aand v3a with lower voltage and 20-kHz frequency due to the phase-shift PWM method wherein each device in the auxiliary inverter switches at 10 kHz. The envelopes of v2a and v3a decrease with capacitor voltages during the acceleration mode.Since the harmonics of the main inverter is cancelled by those of the auxiliary inverters, the total output voltage can realize improved power quality with reduced switching loss. Although the intermediate capacitor voltages may result in asymmetricaladjacent voltage step, the harmonic voltages of synthesizedac output voltage will still concentrate around the quadruple of switching frequency of auxiliary inverters due to the same voltage on capacitors. As a result, it will not degrade the power quality of the synthesized ac output voltage.

V. CONCLUSION:

This paper has proposed a NPC –multilevel(13-level)-inverterbased motor drive system with segmented energy storage elements.In the proposed motor drive system, the energy storagehas 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.A power-distribution strategy between the energy source, the energy storage, and the electric motor has een developed and implemented by a proposed autonomous power regenerative control system. In this control system,the voltage balancing control of the energy storage has been demonstrated to be vital for power distribution, system stability, and reliability. The simulation results and have confirmed thevalidity of the proposed motor drive system. It appears that the proposed motor drive system can be applied to heavyduty electric vehicle and other applications to improve system efficiency, dynamics, and power quality.

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