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A Single-Source Switched-Capacitor Based Step-Up Multilevel Inverter with Reduced Components

Kaibalya Prasad Panda, *Student Member, IEEE*, Prabhat Ranjan Bana, *Student Member, IEEE*, Oleh Kiselychnyk, *Member, IEEE*, Jihong Wang, *Senior Member, IEEE* and Gayadhar Panda, *Senior Member, IEEE*

Abstract— Switched-capacitor based multilevel inverters (SC MLIs) have received a great deal of interest that reduces the dc source requirement and improves the power quality. However, multiple dc sources and requirement of a large number of switches to generate a high-quality boost output are the fundamental issues in the SC MLIs. This paper presents a step-up 17-level SC MLI using reduced number of switches, three capacitors and a single dc source. The steady-state voltage across the capacitors is maintained in the ratio 1:2:0.5 that contributes to quadruple boosting ability without using any auxiliary capacitor voltage balancing circuit. Besides, lower switch count in the conduction path and operation of 50 % of the switches at fundamental frequency ensures total power loss reduction in the proposed circuit. A comparative assessment with recently developed 17-level MLIs in terms of the number of components, gain, stress and cost factor elucidates the advantages of the proposed MLI. After a detailed circuit analysis and loss evaluation, simulations are performed to verify the step-up and inherent balancing features of the proposed MLI. Further, using both the fundamental frequency and high-frequency switching techniques, extensive experimental test results are presented under different transient conditions to validate the operational feasibility of the 17-level prototype.

Index Terms— Multilevel inverter, reduced components, self-voltage balance, single-source, switched-capacitor, voltage gain.

I. INTRODUCTION

Development of multilevel inverters (MLIs) has been a recent trend for a variety of low, medium and high-power applications [1]–[5]. This is due to the competence of MLI in generating a sinusoidal-like output using the combination of switches and dc sources. Diodes and capacitors are the additional components used in the MLI to strengthen structural flexibility. MLIs are used in different applications that include photovoltaic (PV) systems, electric vehicles, STATCOM, traction drives, high-frequency power distribution, etc. [5]–[7] to enhance the power quality, efficiency and reliability. Popular MLI topologies are the neutral-point clamped (NMLI), flying-capacitor MLI (FMLI) and cascaded H-bridge MLI (CMLI). Both the NMLI and FMLI are subjected to voltage balancing problems and collapsing of the whole module due to the series connection of switches [6], [8]. CMLI, on the other hand omits the requirement of additional clamping diodes/capacitors. However, the requirement of large number of semiconductor devices remains a concern in these MLIs for generating higher voltage levels at the output. Based on the requirement and application, CMLI can be operated using equal (symmetrical), unequal (asymmetrical) and varying dc sources [9], [10].

Symmetrical MLIs have simpler control while the asymmetrical structures can increase the voltage levels using less number of dc sources. The CMLI structure in [5] is equipped with capacitors in one of the modules to reduce the number of dc sources. Even though this circuit creates 5-levels at the output the boosting factor (ratio of the output voltage to input voltage) is still one. The voltage boosting is elemental in PV systems to match the output voltage with the grid/load requirement.

Several structural modifications have been done in recent years to reduce the number of switches, dc sources, and control complexity [7], [11]. These structures can be broadly classified into two types. i.e., reduced source switched-capacitor (SC) based boost type topologies and multi-dc non-boosting MLIs. The switched-source and switched-diode MLIs without the inherent boosting feature are esteemed as the non-boosting type MLIs. Towards an attempt to reduce the number of dc source structures are developed in [12], [13]. The input voltage is equally distributed among the capacitors, which appear across the load and consequently lack the ability to boost the output. Circuit proposed in [14]–[16] for the renewable energy application uses series diodes in the conduction path. Thus, their operation in highly inductive loads is unfeasible. However, the voltage level enhancement integrating a floating capacitor is an additional advantage of the circuit proposed in [14]. An additional switch in [15] can eliminate the voltage spike appearing due to the inductive loads only in the first voltage step. The MLI presented in [17] is suitable for PV systems. However, the circuit requires multiple input sources identical to the conventional CMLI. The above-discussed structures embody a back-end H-bridge for generating the negative levels. Excluding the full bridge, potential non-boosting structures are disclosed in [18]–[20], which reduces the voltage stress significantly.

Apart from this, significant research interest is growing in recent years to develop SC MLIs with inherent boosting ability. Voltage balancing of SCs without auxiliary sensors and voltage boosting without additional inductor/transformers makes the SC MLIs suitable for the PV applications and high-frequency ac power distribution [8], [21]–[23]. The MLI topologies presented in [24]–[26] uses the same basic unit to generate high output voltage levels using reduced number of components. The basic unit consisting of one dc source and a capacitor can create a two-step twofold boosted output. The charging of the capacitor in parallel and discharging in series with the source enables self-voltage balancing. Single-phase extension of these circuits requires more number of dc

sources. On the other hand, this offers an opportunity to increase the voltage levels (17-level, 25-level, 49-level, 81-level) by operating the MLI in symmetrical as well as asymmetrical modes. A novel basic module proposed in [27] synthesizes 9-level twofold boost output using a single dc source. However, the extended version of this structure requires multiple dc sources. SC MLI introduced in [28] requires a number of series-connected dc sources to obtain the desired output. The basic module of the disclosed structure in [29] can produce three-fold three-step output. However, the switch count and the number of dc source increase when high-quality voltage is intended to produce at the output.

Most recent research also involves the design of SC MLIs with single input even in the extended forms. Charging spike in SCs is addressed in [23] by developing such MLI with a quasi-resonant front-end structure integrated with a back-end full-bridge. All the capacitors are equally charged and the input voltage is divided among the capacitors. Consequently, this topology lacks in boosting the voltage. The MLI circuits proposed in [30], [31] reduce the voltage stress satisfyingly at the cost of a large number of circuit components. Research effort is also made in [32] to develop a single-dc hybrid NMLI based structure to reduce the stress on the switches while generating 7-level, 9-level and 11-level output. However, the voltage gain in 11-level inverter is limited to 2.5 times the input voltage. Recently configured MLIs in [22], [33], [34] attains high voltage gain (6 times, 4 times and 3 times) using lower number of components. Conventional H-bridge is not required in these circuits to generate the ac voltage output. Including further extension to the 9-level circuit proposed in [22] towards voltage quality improvement using a lower number of components, an improved SC MLI is proposed in this work with the following prominent features:

- i. Single dc source is required to generate a 17-level output.
- ii. Only 12 switches and three capacitors are used in the circuit.
- iii. The capacitor voltages are self-balanced without auxiliary sensors/closed-loop controller.
- iv. Four times boosting ability of the circuit ($V_o = 4V_{in}$).
- v. More than 50 % of switches operate at a low frequency; as a result switching loss is reduced.
- vi. The proposed circuit can adequately operate under any loading power factor (PF).

The next section introduces the proposed topology as well as the capacitor sizing and self-balancing mechanism. The power loss analysis is discussed thoroughly in Section III. A comparison with the recent-art MLIs in Section IV confirms the structural advancement. Followed by a detailed discussion on the modulation scheme in Section V, Sections VI and VII present extensive simulation and experimental investigation, respectively to validate the workability of the 17-level SC MLI. Concluding remarks are provided in Section VII.

II. SC MLI TOPOLOGY AND ITS OPERATIONAL PRINCIPLES

The proposed 17-level SC MLI circuit is shown in Fig. 1. The proposed circuit consists of 12 switches (S_1 - S_{12}), three

capacitors (C_1 - C_3), two diodes (D_1 & D_2) and a single dc power supply (V_{in}). All the switches have an anti-parallel diode connected across it. The circuit produces a 17-level quadruple boost output ($0, \pm 0.5V_{in}, \pm 1V_{in}, \pm 1.5V_{in}, \dots, \pm 4V_{in}$) without using an H-bridge for changing the polarity. The switch pairs S_1 - S_2 and S_{11} - S_{12} are complementary, thus reduces the control complexity. The switches S_5 - S_{10} operates in fundamental frequency and switch pair S_3 - S_4 operates at lower frequency, which results in low switching losses. In addition, the voltage stress across each switch in Fig. 1 implies only three switches S_8 - S_{10} withstands peak load voltage stress. The ratio of voltage across the capacitors C_1 , C_2 , and C_3 ($V_{C1}:V_{C2}:V_{C3}$) is naturally maintained at 1:2:0.5 in the steady-state. To verify the inherent balancing of the capacitors, the operation of the 17-level SC MLI is analyzed hereafter.

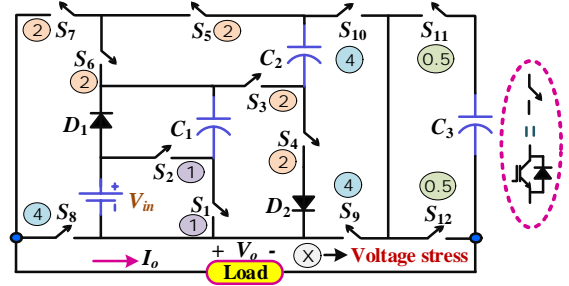


Fig. 1. Proposed 17-level SC MLI topology

In the positive half-cycle of the output voltage, the first voltage step ($+0.5V_{in}$) is produced by discharging only the capacitor C_3 . The second voltage step ($+V_{in}$) is produced by including the source voltage in the load current path and bypassing the capacitor C_3 . During this, the diode D_1 is in forward conduction and the voltage across the capacitor C_1 is clamped to V_{in} by turning on the switch S_1 . By additionally turning on the switch S_{11} , the capacitor C_3 voltage is again added with the input voltage and thus, $+1.5V_{in}$ is obtained at the load. In the next level ($+2V_{in}$), the capacitor C_1 discharges to the load in series with V_{in} by turning on switch S_2 and C_2 is charged during this instant by triggering the switch S_4 . The diode D_2 is connected to avoid unwanted discharging of the capacitor C_2 . The voltage steps $+2.5V_{in}$ and $+3.5V_{in}$ are obtained by discharging the capacitor C_3 as mentioned earlier. Discharging of C_2 in series with the source produces $+3V_{in}$ at the output and the load voltage becomes $+4V_{in}$ when both the capacitors (C_1 and C_2) discharge in series with the source. In the negative half-cycle, the voltage steps $-V_{in}$, $-2V_{in}$, $-3V_{in}$, and $-4V_{in}$ are produced similarly by turning on the switches (S_8 , S_{10} , S_{12}) instead of the switches (S_7 , S_9 , S_{11}). The capacitor C_3 is charged during the intermediate voltage levels $-0.5V_{in}$, $-1.5V_{in}$, $-2.5V_{in}$, and $-3.5V_{in}$. It is also worth noting that there always exists a path for the reverse flow of current, which facilitates successful operation of the proposed circuit under different load PF.

Table I presents the switching states to synthesize the 17-level output with any loading PF and the output waveform of the proposed SC MLI with capacitor charging-discharging pattern is shown in Fig. 2(a). Fig. 2(b) shows the capacitors C_1 charges in parallel with the dc source to V_{in} and discharges in

series with the source. The capacitor C_2 is charged in parallel with $V_{in}+V_{C1}$ and discharges in series the accumulated energy ($2V_{in}$) to the load as depicted in Fig. 2(c). The capacitor C_3 is discharged in the whole positive half-cycle and charged symmetrically in the negative half-cycle, thus maintaining

$0.5V_{in}$ voltage across it. Fig. 2(d) shows the equivalent circuit and conduction path during the intermediate voltage steps in the positive and negative cycle. Thus, the natural balancing ability of all the three capacitors is confirmed.

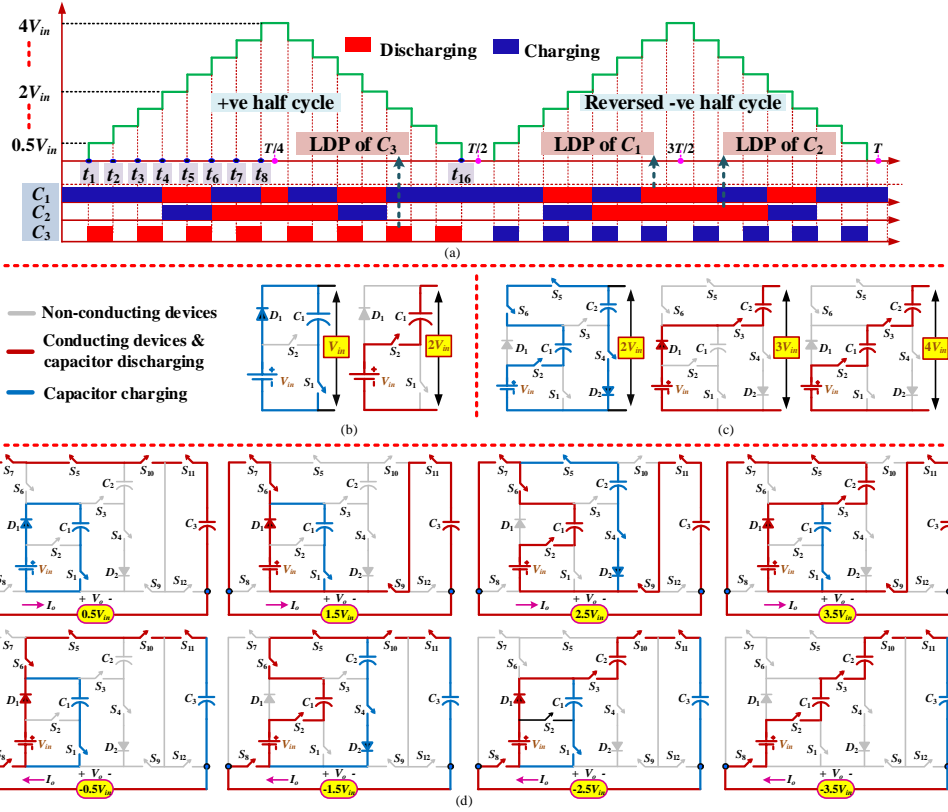


Fig. 2. Operation of the proposed circuit (a) output pattern of the proposed SC MLI, charging-discharging operation of (b) C_1 , (c) C_2 , (d) C_3

TABLE I
SWITCHING PATTERN OF THE PROPOSED 17-LEVEL SC MLI

Conducting switches in Positive half-cycle	Voltage steps	Conducting switches in Negative half-cycle
$S_1 - S_5 - S_7 - S_{10} - S_{12}$	0	$S_1 - S_8 - S_9 - S_{12}$
$S_1 - S_5 - S_7 - S_{10} - S_{11}$	$\pm V_{in}/2$	$S_1 - S_5 - S_6 - S_8 - S_{10} - S_{11}$
$S_1 - S_5 - S_6 - S_7 - S_9 - S_{12}$	$\pm V_{in}$	$S_1 - S_5 - S_6 - S_8 - S_{10} - S_{12}$
$S_1 - S_5 - S_6 - S_7 - S_9 - S_{11}$	$\pm 3V_{in}/2$	$S_2 - S_4 - S_6 - S_8 - S_{10} - S_{11}$
$S_2 - S_4 - S_6 - S_7 - S_9 - S_{12}$	$\pm 2V_{in}$	$S_2 - S_4 - S_6 - S_8 - S_{10} - S_{12}$
$S_2 - S_4 - S_6 - S_7 - S_9 - S_{11}$	$\pm 5V_{in}/2$	$S_1 - S_3 - S_6 - S_8 - S_{10} - S_{11}$
$S_1 - S_3 - S_5 - S_7 - S_9 - S_{12}$	$\pm 3V_{in}$	$S_1 - S_3 - S_6 - S_8 - S_{10} - S_{12}$
$S_1 - S_3 - S_5 - S_7 - S_9 - S_{11}$	$\pm 7V_{in}/2$	$S_2 - S_3 - S_8 - S_{10} - S_{11}$
$S_2 - S_3 - S_5 - S_7 - S_9 - S_{12}$	$\pm 4V_{in}$	$S_2 - S_3 - S_8 - S_{10} - S_{12}$

A. Steady-state switched-capacitor analysis

Fig. 2(a) implies that the overall charging time of the capacitors is significantly lower than the total output voltage duration, attesting quick recovery of the capacitor voltages after the discharging period. The low parasitic resistance path and adequate charging instant further warrant retaining the desired capacitor voltage. To select the suitable capacitance, different factors, i.e., the largest discharging period (LDP) duration of the capacitors (C_1 & C_2), total discharging time in the whole positive half cycle (C_3), nominal frequency, lower voltage ripple and type of loading, are considered. Assuming equal duration for all the voltage steps, the discharging amount of the capacitors C_1 - C_3 can be expressed as in (1)-(3) considering φ is the lagging angle between the load current

(I_o) and fundamental voltage where the peak fundamental load current is I_{omax} .

$$\Delta Q_{C1} = 2 \int_{t_7}^{T/4} I_{omax} \sin(\omega t - \varphi) dt \quad (1)$$

$$\Delta Q_{C2} = 2 \int_{t_5}^{T/4} I_{omax} \sin(\omega t - \varphi) dt \quad (2)$$

$$\Delta Q_{C3} = 4 \int_{t_1}^{t_2} I_{omax} \sin(\omega t - \varphi) dt \quad (3)$$

Further, based on the fundamental frequency switching output voltage shown in Fig. 2(a), one half-cycle ($T/2$) can be divided into sixteen time steps (t_1 - t_{16}) and therewith t_1 , t_2 , t_5 and t_7 (in sec) are expressed in (5) using (4) [29]:

$$t_i = \frac{\sin^{-1}\left(\frac{i-0.5}{N_s}\right)}{\omega} = \frac{\sin^{-1}\left(\frac{2i-1}{N_l-1}\right)}{\omega} \quad (4)$$

where N_s is the number of voltage steps and N_l is the number of levels in the output.

$$\begin{aligned} t_1 &= \frac{\sin^{-1}(1/16)}{\omega}, t_2 = \frac{\sin^{-1}(3/16)}{\omega}, t_3 = \frac{\sin^{-1}(5/16)}{\omega}, t_4 = \frac{\sin^{-1}(7/16)}{\omega} \\ t_5 &= \frac{\sin^{-1}(9/16)}{\omega}, t_6 = \frac{\sin^{-1}(11/16)}{\omega}, t_7 = \frac{\sin^{-1}(13/16)}{\omega}, t_8 = \frac{\sin^{-1}(15/16)}{\omega} \end{aligned} \quad (5)$$

The corresponding voltage ripple (ΔV_{rC}) is expressed in (6) and capacitance is given in (7) considering $k\%$ voltage ripple in the capacitors.

$$\Delta V_{rC} = \frac{\Delta Q_C}{C} \quad (6)$$

$$C_1 \geq \frac{\Delta Q_{C1}}{kV_{in}}, C_2 \geq \frac{\Delta Q_{C2}}{k(2V_{in})} \text{ and } C_3 \geq \frac{\Delta Q_{C3}}{k(0.5V_{in})} \quad (7)$$

Applying (1), (2), (3) and (5), the capacitance is finally expressed in (8), (9) and (10).

$$C_1 \geq \frac{I_{o\max}}{k\omega V_{in}} [\cos(0.9484 - \varphi) - \sin \varphi] \quad (8)$$

$$C_2 \geq \frac{I_{o\max}}{k\omega V_{in}} [\cos(0.5974 - \varphi) - \sin \varphi] \quad (9)$$

$$C_3 \geq \frac{8I_{o\max}}{k\omega V_{in}} [\cos(0.0625 - \varphi) - \cos(0.1886 - \varphi)] \quad (10)$$

Using the series-parallel charge balancing principle and with the selected values given in (8) and (9) considering $k\%$ of voltage ripple, the capacitors C_1 and C_2 naturally maintain the voltage in a 1:2 ratio. However, capacitors C_3 symmetrically discharge and charge in the positive and negative half-cycles, respectively. Thereby, the self-balancing nature of C_3 can also be verified considering any intermediate voltage steps. For instance, consider the equivalent circuit shown in Fig. 3 for the synthesis of $\pm 2.5V_{in}$ output voltage. The net charge (ΔQ_{C3}) is zero, which can be expressed as follows:

$$\Delta Q_{C3} = [I_{C3}(+) - I_{C3}(-)]T \quad (11)$$

where I_{C3} is the current flowing through the capacitor C_3 . Assuming the net impedance Z , following expressions are derived from the equivalent circuit.

$$I_{C3}(+) = \frac{V_{in} + V_{C1} - V_o + V_{C3}}{Z} = \frac{2V_{in} - V_o + V_{C3}}{Z} \quad (12)$$

$$I_{C3}(-) = \frac{V_{in} + V_{C2} + V_o - V_{C3}}{Z} = \frac{3V_{in} + V_o - V_{C3}}{Z} \quad (13)$$

Using (12) and (13), $\Delta Q_{C3} = \left[\frac{2V_{C3} - V_{in}}{Z} \right] T$ and hence, $V_{C3} = 0.5V_{in}$ at the steady-state.

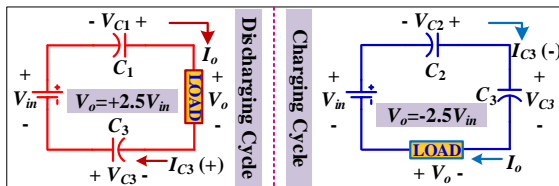


Fig. 3. Equivalent circuit of proposed circuit during $V_o = \pm 2.5V_{in}$

The above deduction demonstrates the inherent voltage balancing and selection process of suitable capacitance in the proposed SC MLI. Considering about 5-7% of voltage ripple, the proposed circuit is developed and examined further.

III. POWER LOSS EVALUATION FOR THE PROPOSED CIRCUIT

Switching loss (P_{sl}), ripple loss (P_{rl}), and conduction loss (P_{cl}) are the three major losses associated with the SC boost type MLIs [23], [29], [31]. These losses are evaluated in the following sections for the proposed 17-level MLI.

A. Switching loss

The time delay between the transitions of a switching state produces switching power loss (P_{sl}). The blocking voltage (V_B) across a semiconductor switch during its off-state charges the built-in parasitic capacitor (C_p) linearly. Further, C_p discharges from the magnitude V_B to zero during the on-state of the switch. Therefore, the energy loss (E_{sl}) by a semiconductor switch for one transition state can be evaluated using (14). Thereby the switching power loss during the switching actions can be calculated using (15).

$$E_{sl} = \frac{1}{2} C_p V_B^2 \quad (14)$$

$$P_{sl} = f_s E_{sl} = \frac{1}{2} f_s C_p V_B^2 \quad (15)$$

As can be noted from Fig. 1, the switches S_5 - S_{10} block sum-total voltage stress of $18V_{in}$ and operate in a fundamental frequency (considering purely resistive loading). Thus, considering f_s and f_o as the switching and fundamental frequencies, (15) can be further simplified as follows:

$$P_{sl} = \frac{1}{2} C_p V_{in}^2 [18f_o + 7f_s] \quad (16)$$

B. Ripple loss

Internal resistances of the capacitor and semiconductor devices that are in the charging path of capacitors (C) generate ripple loss in the SC MLI. The voltage difference (ΔV_c) between the actual and desired voltage of the capacitor is the key influencing parameter of the ripple energy loss (E_{rl}) that is evaluated in terms of the charging time (t_c) and charging current (I_c).

$$\Delta V_c = \frac{1}{C} \int_0^{t_c} I_c(t) dt \quad (17)$$

$$E_{rl} = \frac{1}{2} C \Delta V_c^2 \quad (18)$$

From (17) and (18), the ripple power loss (P_{rl}) can be calculated by (19). It can be observed that the larger value of the capacitance can minimize the P_{rl} . However, a trade-off is vital between the sizing and the ripple loss due to capacitors.

$$P_{rl} = f_o E_{rl} = \frac{f_o}{2C} \left[\int_0^{t_c} I_c(t) dt \right]^2 \quad (19)$$

C. Conduction loss

The loss incorporated by the parasitic elements of the conducting devices in the load current path results in the conduction loss (P_{cl}). Fig. 4 shows the generalized equivalent

circuit for the proposed MLI for synthesizing any voltage level. Therein, the output current expression (I_o) is given by (20).

$$I_o = I_{omax} \sin \omega t = \frac{m_i V_{omax}}{Z_l} \sin \omega t \quad (20)$$

where m_i is the modulation index, which is the ratio of reference voltage (desired value) to the maximum obtainable fundamental voltage and Z_l is the load impedance. The conduction loss can be evaluated by considering the duration of each voltage level. For instance, the time duration (t_1 - t_2) in Fig. 2(a) represents the voltage level $0.5V_{in}$. Consequently, the energy loss is expressed in (21), considering the on-state switch resistance (R_s), the internal resistance of the capacitor (R_c), and forward voltage drop of the diode (V_D).

$$E_{cl(0.5V_{in})} = \int_{t_1}^{t_2} I_o^2 (4R_s + R_c) dt \quad (21)$$

The diode voltage drop is not included in (21) as it is in reverse bias during $0.5V_{in}$. Consequently, the total conduction loss of the proposed MLI considering all the voltage levels is

$$P_{cl} = 8f_o \sum_{i=0.5,1,\dots,4} E_{cl}(iV_{in}) \quad (22)$$

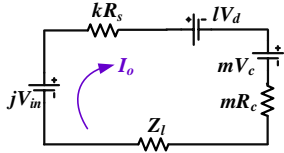


Fig. 4. Generalized equivalent circuit of the proposed MLI

Taking into account the losses derived in (16), (19) and (22), the power losses and overall efficiency of the proposed MLI are evaluated in Section VI using (23).

$$\eta = \frac{\text{output power}}{\text{output power} + P_{sl} + P_{rl} + P_{cl}} \quad (23)$$

TABLE II

COMPARISON OF THE SYMMETRICAL 17-LEVEL MLI TOPOLOGIES

Parameters		N_{dc}	N_{sw}	N_{dr}	N_{dd}	N_{cap}	N_{ms}	MSV (x V_{in})	TSV (x V_{in})	Gain	C_f ($\delta=0.5$)	C_f ($\delta=1.5$)	Full- bridge		
Switched- dc/diode	Non-boosting	[12]	4	20	20	0	8	10	8	48	1	14.35	15.76	YES	
		[14]	6	9	9	3	1	6	4	20	1	10.76	12.53	YES	
		[15]	8	13	13	8	0	10	8	8	47	1	22.09	24.85	YES
		[17]	8	20	20	0	0	10	8	8	48	1	24.94	27.76	YES
		[18]	8	18	18	0	0	9	8	8	36	1	22.24	24.35	NO
		[19]	8	18	18	0	0	9	2	32	1	22.12	24	NO	
Switched-capacitor	Boosting	[23]	1	18	18	8	8	10	8	56	1	3.85	4.26	YES	
		[24]	4	24	24	4	4	12	2	40	2	16.59	17.76	YES	
		[25]	2	18	18	6	6	8	8	44	4	6.91	7.56	NO	
		[26]	4	20	20	4	4	10	8	40	2	14.24	15.41	NO	
		[27]	2	18	14	2	4	6	4	40	2	5.47	6.06	NO	
		[29]	2	18	18	2	6	7	8	58	4	6.43	7.28	NO	
		[30]	1	39	39	0	7	16	1	39	8	6.08	6.37	NO	
[31]	1	20	16	0	5	10	2	21.5	4	3.16	3.47	NO			
Proposed		1	12	12	2	3	6	4	25	4	2.30	2.67	NO		

Total standing voltage (TSV) and maximum standing voltage (MSV) are further evaluated for MLI topologies. TSV is calculated taking into account voltage stress across all the switches. Proposed MLI reduces the TSV to a great extent as

IV. COMPARATIVE EVALUATION

To assess the advantages of the proposed SC MLI, a comparison is carried out in Table II with recently developed 17-level MLI topologies based on different parameters and taking into account symmetrical configurations. As stated earlier, the compared topologies are categorized into two broad categories. The switched-dc or switched-diode based circuits basically consist of multiple dc sources and do not possess the boosting ability. The SC-based topologies reduce the source count and feature the boosting ability. A number of capacitors and switches are used in such circuits to produce a high-quality output voltage. However, the proposed circuit aims at reducing the number of components to produce a 17-level output.

Except the MLI proposed in [23], the required number of dc sources (N_{dc}) in all the non-boosting structures is more than one. Most of the SC MLIs also require multiple input sources when extended to create 17-level output, unlike the proposed MLI. In view of least number of switches (N_{sw}) and drivers (N_{dr}), the proposed circuit ranks first among other SC MLIs. The MLI disclosed in [14] involves fewer switches and drivers but at the cost of large number of dc sources. The single dc SC MLIs [30] and [31] do not require discrete diodes (N_{dd}), but involve a large number of switches. On the contrary, the proposed 17-level topology uses only two diodes. Although the use of capacitors supports voltage boosting, the inrush current increases with increase in number of capacitors. Lower number of capacitors (N_{cap}) in the proposed circuit limits the inrush current and increases the reliability. More number of switches in the conducting path increases the power loss. The proposed MLI is also superior among all the MLI topologies on account of maximum number of switches in the conduction (N_{ms}) for 17-level operation.

the conventional full-bridge is avoided for producing ac output. The MLIs proposed in [31] and [14] have the minimum TSV. However, the former requires almost double the number of switches than the proposed MLI and the latter is

a multi-dc topology that lacks the boosting ability. Proposed MLI has a quadruple boosting gain using minimum number of switches. Besides, cost factor (C_f) is chosen as a parameter to establish the design superiority which is defined as,

$$C_f = \frac{(N_{sw} + N_{dr} + N_{dd} + N_{cap} + N_{ms} + \delta \cdot TSV_{pu}) N_{dc}}{N_l} \quad (24)$$

The C_f is evaluated considering different values of the weightage coefficient δ (low for more weightage to the number of components and high for more weightage to the TSV). The proposed MLI has the least C_f among the other MLIs under both the conditions ($\delta = 0.5$ and 1.5). Hence, the proposed MLI is a suitable alternative to the recently developed MLIs for obtaining high-quality output using least switch count.

V. MODULATION SCHEME

Fundamental switching control and high frequency switching control are the two main categories of PWM control schemes generally employed to verify the MLI working. Selective harmonic elimination switching control (SSC) is one of the former category of control schemes which aggressively eliminates the targeted lower order dominant harmonics and thereby maintains the highest quality of output waveforms [9], [11], [14], [16]. The fundamental component of staircase output voltage waveform in terms of Fourier series equations can be expressed as in (25), which is valid for any single-phase MLI.

$$V_1 = \frac{4V_d}{\pi} \{ \cos n\alpha_1 + \dots + \cos n\alpha_p \} \sin(n\omega t) \quad (25)$$

Here α_p (proportional to t_i), n , and V_d are the symbolic representation of switching angles, order of harmonics, and nominal value of the dc voltage, respectively. Further, p is directly associated with the number of voltage levels (N_l) as;

$$p = (N_l - 1)/2 \quad (26)$$

For any voltage level, the switching angle values can be determined within the modulation index (m_i) range of [0, 1] to eliminate the targeted lower order harmonics from the system, and thus it can be regarded as the key control parameter. The expression of m_i in terms of the fundamental and nominal dc voltage is given as follows:

$$m_i = \frac{\pi V_1}{(4pV_{d1})}, 0 \leq m_i \leq 1 \quad (27)$$

The proposed MLI is designed to output a 17-level staircase voltage waveform. Considering the expressions (25) & (27), the associated non-linear equations for the MLI are given in (28) with the target to eliminate the 3rd to 15th order harmonics. To extract the optimal solutions (α_p), particle swarm optimization algorithm (PSO) is employed taking into account the angle constraint in (29) and fitness function given in [16].

$$\begin{cases} \cos \alpha_1 + \dots + \cos \alpha_8 = 8m_i \\ \cos 3\alpha_1 + \dots + \cos 3\alpha_8 = 0 \\ \vdots \\ \cos 15\alpha_1 + \dots + \cos 15\alpha_8 = 0 \end{cases} \quad (28)$$

$$0 < \alpha_1 < \alpha_2 < \dots < \alpha_8 \leq \pi/2 \quad (29)$$

Moreover, the performance of the optimization process for the proposed MLI can be verified from Fig. 5. Corresponding to the minimum value of the fitness function (*i.e.*, in the range 0.9-0.94), switching angles are selected to verify the operation of the proposed circuit. Figure also implies that the total harmonic distortion (THD) level decreases with the increase in m_i and also the fundamental value is retained at the desired level even under a lower m_i value. This is one of the dominant features of the SSC technique and thus, the number of levels in the output voltage and current does not reduce with the decrease in m_i although an increase in THD can be expected in such scenario. Besides the optimum values of the switching angles are chosen corresponding to the minimum fitness function value, a lower m_i value of 0.3 is taken as reference to verify the SSC principle in next Section.

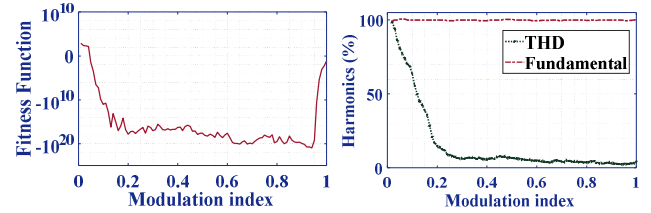


Fig. 5. Fitness function and THD evaluation using SSC technique

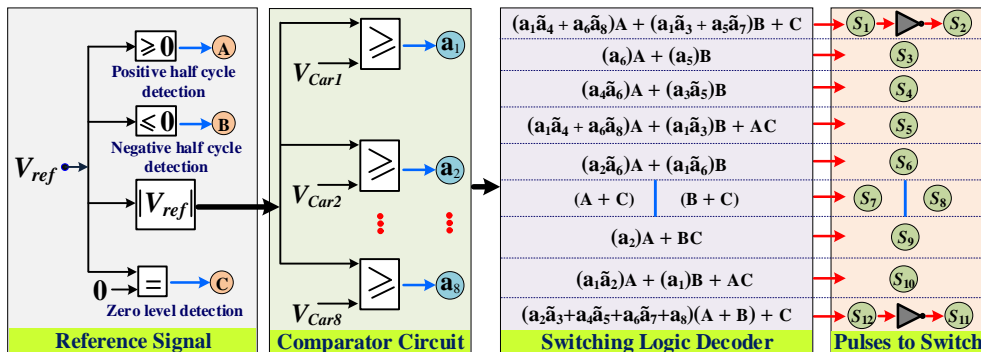


Fig. 6. Block diagram of PPC scheme with switching logic

The fundamental frequency SSC scheme maintains the required fundamental value of the output and thus cannot regulate the ac output (or the voltage gain), which is generally required in different application of an MLI. In such a case, the phase-disposition PWM control (PPC) scheme [14], [19], [33] may be employed. In the PPC scheme, multiple carrier signals are compared with the reference sinusoidal signal to generate the PWM signals through the pulse logic decoder as shown in Fig. 6. In the decoder circuit, the switching logic presented in Table I is synthesized through the appropriate combination of logic gates. The PPC scheme doesn't involve any complex equations to retain the fundamental component, unlike the SSC technique. Nevertheless, the conversion ratio of the proposed circuit can be varied in the range of $0.5V_{in}$ to $4V_{in}$ by varying the m_i .

VI. SIMULATION ANALYSIS

The proposed 17-level MLI consisting of 12 IGBT switches is simulated in MATLAB/Simulink environment. The input dc source is considered 100 V and the inverter is operated with a 50 Hz nominal frequency unless otherwise specified. The capacitance values are accordingly calculated using (8)-(10) and C_1 , C_2 , and C_3 are chosen as 3300 μF , 4700 μF , and 2200 μF , respectively. Using the SSC technique, the eight switching angles corresponding to different m_i are saved in a look-up table for the generation of switching pulses.

To validate the 17-level operation using the SSC technique, first the results are obtained in Fig. 7(a) under dynamically varying m_i condition at constant loading of 90 Ω . The 17-level output is acquired even with low m_i due to fundamental switching SSC principle, whereas the THD in the load voltage reduces (See Fig. 7(b)) with the increase in m_i . Quadruple step-up ability with the inherent balancing of capacitor voltages V_{C1} , V_{C2} and V_{C3} are in accordance with the theoretical analysis. Fig. 7(c) verifies the working under a change in load PF with the change in loading from 90 Ω -108 mH to 120 Ω -108 mH. The capacitor voltage ripple decreases with an increase in R value for a fixed C_1 , C_2 , and C_3 . The capacitor voltages inherently settle to the original value under sudden variation in input from 80 V to 100 V as shown in Fig. 7(d), which verifies the successful performance of the proposed SC MLI. Fig. 7(e) depicts the voltage ripple decreases considerably and the load current drops due to an increase in frequency from 50 Hz to 150 Hz (switching angles corresponding to 150 Hz are also saved in look-up table) in presence of inductive loading. Evidently, the proposed MLI can act as a potential high-frequency ac source for different applications. Fig. 7(f) shows the voltage stress across all the unidirectional switches are in accordance with Fig. 1. It is also apparent that apart from switches S_1 , S_2 , S_{11} and S_{12} , all other switches operate at a low frequency, which thus results in low power loss in the circuit.

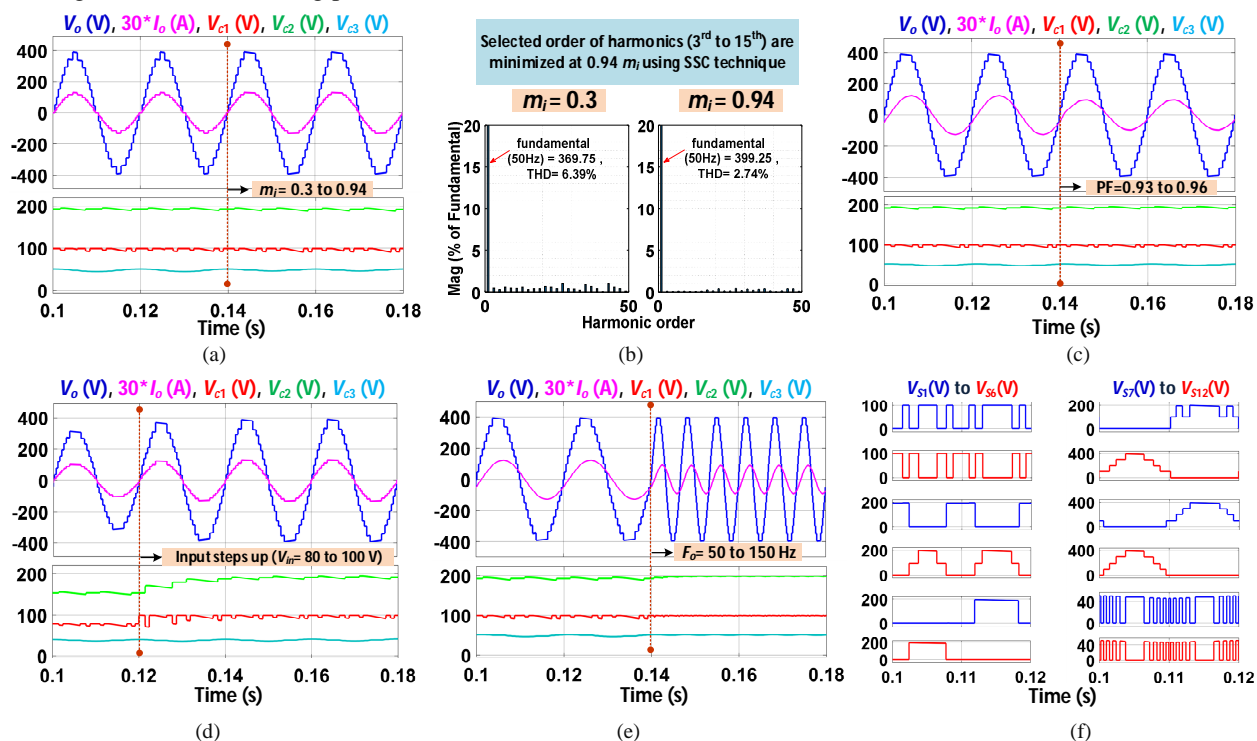


Fig. 7. Simulation analysis, (a) Change in modulation index, (b) Harmonic analysis of the load voltage, (c) Change in loading PF, (d) Change in input voltage, (e) Change in nominal frequency, (f) Voltage stress across all the switches

VII. EXPERIMENTAL VERIFICATION

To verify the suitable real-time operability, a test setup of the proposed 17-level MLI is developed in the laboratory. A

programmable dc supply is initially set to 100 V. As the output voltage is boosted to four-times the input, the RMS value of the load voltage is about 280 V. IGBT switches 12N60A4D with integrated anti-parallel diodes are considered

for S_1 - S_{12} and two MUR860 is used as D_1 and D_2 . Selected values of the capacitance (C_1 - C_3) are same as in simulation with internal resistances 36 m Ω , 18 m Ω and 54 m Ω , respectively. A DSP controller with Simulink interfacing is used to produce the switching pulses of (0-5) V. An isolated driver circuit built using TLP250 is then used to amplify these pulses (about 20 V) which drive the switches. In addition, the driver circuit also provides adequate isolation between the power circuit and control circuit. A ScopeCoder (DL850E) is used to capture the voltage-current waveforms and the performance parameters are obtained using a WT1800 power analyzer.

Identical to the result shown in Fig. 7(a), experimental outputs are obtained with a change in m_i and with fixed resistive loading of 90 Ω in Fig. 8(a). The desired 17-level output is obtained with a change in switching pulse in conjunction with variation in m_i from 0.3 to 0.94. Further, tests follow considering higher m_i value (0.94). The RMS value of load current varies from 2.9 A to 3.9 A and the PF varies from 0.93 to 0.85 as the load changes from 90 Ω -108 mH ($RL-1$) to 60 Ω -120 mH ($RL-2$) in Fig. 8(b). The output voltage and capacitor voltages are undistorted during the sudden load

transient. Self-balancing of the capacitors in both Fig. 8(a) & (b) is obtained due to appropriate charging-discharging. Herein the capacitor currents and the source current are depicted in Fig. 8(c) with 90 Ω load, which implies symmetrical charging pattern of the capacitors in a full cycle. The current spikes are reduced using a small inductor (0.03 mH) in the charging loop that is not shown in the circuit analysis for the sake of simplification. The captured power analyzer results in Fig. 8(d)-(g) shows the change in active-reactive power (P, Q), PF (λ), phase angle (Φ), efficiency (η_1), voltage THD and current THD. Fig. 8(d) and (e) are obtained in accordance with Fig. 6(a) at fixed resistive loading and change in m_i . The THD varies with the change in m_i . Fig. 8(f) and (g) are obtained in accordance with Fig. 8(b) with a change in load from $RL-1$ to $RL-2$. A proportional increase in the active power and change in efficiency is witnessed with decrease in the impedance and PF. Fig. 8(h) and (i) further verify the self-balancing and step-up abilities of the proposed circuit with sudden variation in input voltage (90 V to 100 V) and output frequency (150 Hz to 50 Hz), respectively. Similar observation as in Fig. 7(f), the voltage stress on switches is testified in Fig. 8(j).

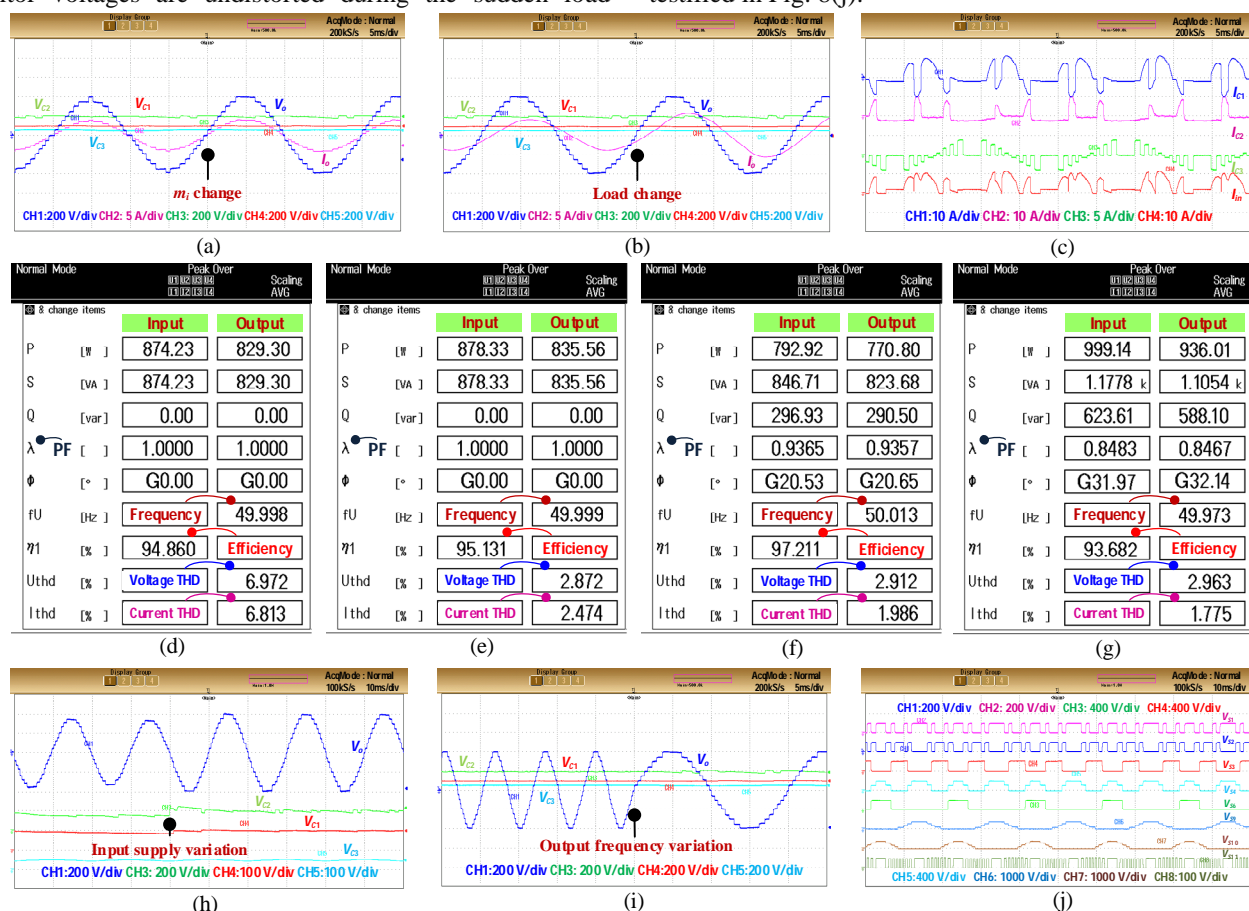


Fig. 8. Experimental output voltage & current waveform (a) Sudden variation in m_i , (b) Change in loading PF, (c) Current through the capacitors and input current, (d) Parameters at $m_i = 0.3$, (e) Parameters at $m_i = 0.94$, (f) Parameters under $RL-1$, (g) Parameters under $RL-2$, (h) Input supply step-up, (i) Sudden change in output frequency, (j) Voltage stress across ($S_1, S_2, S_3, S_4, S_6, S_9, S_{10}, S_{11}$)

To verify the adequate operation of the proposed circuit, experimental tests are further performed with PPC technique considering a switching frequency and nominal frequencies of

2 kHz and 50 Hz, respectively. Initially, the proposed inverter produce a 13-level output with 0.6 m_i and desired 17-level output is obtained as shown in Fig. 9(a) once the m_i is changed

to unity. Fig. 9(b) ascertains a clean sinusoidal load current, undistorted load voltage and self-balanced capacitor voltages with a change in loading from $RL-1$ to $RL-2$ under the PPC scheme. The efficiency of the prototype is further evaluated

with corresponding output power considering pure resistive loading of $90\ \Omega$. It is clear from Fig. 9(c) that the switching power loss, conduction loss and the ripple losses increase with an increase in the output power.

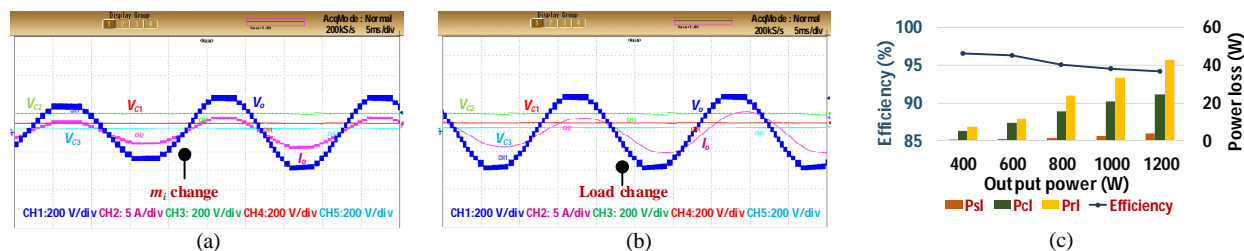


Fig. 9. Experimental verification of the proposed MLI with PPC scheme (a) Change in m_i , (b) Change in loading PF, (c) Efficiency and loss evaluation

VIII. CONCLUSION

This work introduced a reduced switch single-source SC MLI with quadruple boosting ability. Using only 12 switches and 3 capacitors, the proposed MLI is able to synthesize a 17-level output with a reduced number of devices in the conducting path. The capacitors C_1 and C_2 can inherently balance the voltage in 1:2 ratios using the series-parallel charge balancing principle and the capacitor C_3 self-regulates the voltage at $0.5V_{in}$ due to symmetrical charging-discharging in a full cycle. Thus, the use of auxiliary voltage balancing circuit/sensors is avoided. The operating principles, voltage balancing ability, steady-state analysis of the SCs and power loss evaluation have been addressed thoroughly. The comparative assessment with recent-art 17-level structures demonstrates the benefits on lower number of components, minimum cost factor and no requirement of polarity reversal H-bridge. Simulation and experimental investigations of the 17-level MLI under change in m_i , sudden change in supply voltage, change in PF and frequency variation fully testifies the structural operability. Moreover, high step-up operation with adequate inherent voltage balancing without additional dc-dc converter makes the proposed MLI suitable for PV applications.

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Kaibalya Prasad Panda (S'18) received the B.Tech. degree in electrical and electronics engineering from the Dr. M.G.R. University, Chennai, India, in 2011 and the M.Tech. degree in power electronics and drives specialization from the KIIT University, Bhubaneswar, India, in 2013. He is currently working toward the Ph.D. degree with the Department of Electrical Engineering,

National Institute of Technology Meghalaya, Shillong, India. His research interests include reduced switch multilevel inverter design, power quality control and photovoltaic system applications.

He was a visiting scholar with the University of Warwick, U.K., during January to March 2019, funded through the Joint UK-India Clean Energy (JUICE) two months exchange program scheme. He was recipient of Prof. Subhasis Nandi Student Travel Awards for Power Electronics, Drives and Energy Systems (PEDES 2018) conference and IAS Travel grant for Power Electronics, Smart Grid and Renewable Energy (PESGRE 2020) conference. He is a regular Reviewer of several IEEE and IET Journals.



Prabhat Ranjan Bana (S'19) received the B.Tech. degree in electrical engineering from the PMEC, Berhampur, India, in 2016, and the M.Tech. degree in power and energy systems specialization from the NIT Meghalaya, Shillong, India, in 2019, where he was also a Research Associate from July 2019 to February 2020. He is currently a Ph.D. Scholar in the Department of Electric Power Engineering, NTNU, Norway. His research interests include multilevel inverters, photovoltaic systems, and power quality.



Oleh Kiselychnyk (M'15) received the M.Sc. and Ph.D. degrees in electrical engineering and automation from the National Technical University of Ukraine "Kyiv Polytechnic Institute" (NTUU "KPI"), in 1993 and 1997, respectively. He is currently an Associate Professor in the School of Engineering, University of Warwick, Coventry, U.K. From 2002 until 2012, he was a Docent of the Department of Electrical Drives of NTUU "KPI." He was also a Visiting Fulbright Scholar at the University of Utah, Salt Lake City, UT, USA, in 2009, and a Visiting German Academic Exchange Service Researcher at the Hamburg University of Technology, Hamburg, Germany, in 2008. His main research interests include control of electrical motors and generators, power electronic converters and automation of industrial installations.



Jihong Wang (M'06–SM'12) received her Bachelor's and Master's Degrees in Electrical Engineering from Wuhan University of Technology and Shandong University of Technology, China, respectively. She obtained the Ph.D. degree from Coventry University, U.K., in 1995. She is currently a Professor in Electrical Power and Control Engineering with the School of Engineering, University of Warwick, UK. Her current research interests include nonlinear system control, power system modelling and control, energy storage and grid integration. She was Technical Editor for the IEEE/ASME Transactions on Mechatronics and is Associate Editor to the IEEE Journal of Emerging and Selected Topics in Industrial Electronics.



Gayadhar Panda (M'07–SM'19) received the bachelor's degree in electrical engineering from the Institute of Engineers, Kolkata, India, the Master's degree in power electronics from Bengal Engineering College (presently IEST), Shibpur, India, and the Ph.D. degree in electrical engineering from Utkal University, Bhubaneswar, India, in 1996, 1998, and 2007, respectively. He is currently a Professor with the Department of Electrical Engineering, National Institute of Technology, Meghalaya, India. He has served as Head of the department and Chairman of various committees at institute level. He is also currently looking after Dean academic affairs (AA) at NIT Meghalaya. He has more than 20 years of teaching experience. His current research interests include automatic generation control, stability improvements using flexible alternating current transmission system devices, power quality, power electronic converters, and distributed power generation.