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A Hybrid Multilevel Converter for Medium and High Voltage Applications

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***Abstract*--This paper investigates the suitability of the hybrid multilevel converter for medium and high voltage application. The converter operation, modulation, and capacitor voltage balancing method are described in detail. The ability of the hybrid multilevel converter to operate with different modulation indices and load power factors is investigated. It has been established that the hybrid multilevel converter is capable of operating independent of load power factor. Operation with variable modulation index increases voltage stresses on the converter switches and does not alter the fundamental voltage magnitude as in all known voltage source converter topologies. The viability of the hybrid multilevel converter for medium and high voltage applications is confirmed by simulations.**

***Index Terms*--Hybrid multilevel converter, high-voltage dc transmission systems, modular multilevel converter and pulse width modulation.**

I. INTRODUCTION

Voltage source multilevel converters such as the diode clamped, cascaded with electrically isolated dc sources, flying capacitor and modular converters are attractive in medium and high voltage applications [1-4].

Diode clamped and flying capacitor multilevel converters are limited to medium voltage applications with a few exceptions due to lack of modularity and increased control complexity when extended to a higher number of levels[1-2, 4-6].

Cascaded multilevel converters are used in medium voltage drive systems and reactive power applications. The use of the cascaded multilevel converter in medium-voltage drive systems requires a number of transformers to provide electrically isolated active dc sources [7-10]. This adds cost, losses and increases power circuit complexity.

The modular multilevel converter is attractive in medium and high voltage applications due to its modular structure and can be extended to large number of levels practically feasible without capacitor voltage balancing problems[11-15]. But it requires a number of large capacitors and semiconductors, which may affect converter footprint and losses [12, 16-18].

The voltage source hybrid multilevel converter recently proposed [3] is shown in Fig. 1a and is well suited to medium and high voltage applications. It requires fewer switching devices and capacitors than the modular multilevel converter (M2C) in order to generate the same number of voltage levels. This may result in reduced conversion losses and a small converter footprint. Placement of the chain link capacitors is not directly in the load current path as in the modular converter, may allow use of small capacitors.

This paper investigates the suitability of the hybrid multilevel converter for medium and high-voltage applications. The investigation focuses on the converter ability to operate over all power factors (0~1), full modulation index linear range (0~1.15), switching frequency per device, device voltage and current stresses, and output voltage waveforms quality. Circuit operation, modulation and chain link capacitor voltage balancing strategies are discussed. The practicality of the hybrid multilevel converter in medium–voltage applications is assessed by simulating a 100kW converter with a 0.8kV dc link voltage, controlled using sinusoidal pulse width modulation with a 1.35kHz carrier frequency.

II. HYBRID MULTILEVEL CONVERTER

Fig. 1a shows the three-phase voltage source hybrid multilevel converter with N chain links per limb. At unity modulation index, the voltage across each chain link capacitor must be maintained at $\frac{1}{2}{V_{dc}}/{N}$, where V_{dc} is the total dc link voltage and N is the number of chain link cells per limb. The total voltage across the chain link capacitors of each limb is $\frac{1}{2}V_{dc}$. Hybrid multilevel converter in Fig. 1a exploits the N chain link capacitors in each limb to generate a rectified voltage waveform with $N+1$ voltage levels at the input of each H-bridge cell and with a voltage step of ${V_{dc}}/{N}$ and uses bipolar H-bridge cells at the converter output to generate $2N+1$ voltage levels between $\frac{1}{2}V_{dc}$ and $-\frac{1}{2}V_{dc}$. The H-bridge devices support $\frac{1}{2}V_{dc}$ and commutate at zero crossing. To prevent short circuit during three-phase operation, the hybrid multilevel converter requires three separate single-phase transformers with the converter side isolated as shown in Fig. 1a. In this paper, level shifted carriers arranged in phase disposition (PD) are used with a 1.35kHz switching frequency and modulated with sinusoidal reference voltages.

In the hybrid multilevel converter, voltage balancing of the chain link capacitors is influenced by the current polarity in each limb. Therefore, each voltage level is achieved by selecting an appropriate number of chain link capacitors taking into consideration the voltage magnitude of the capacitors and current polarity in each limb. Fig. 1b summarizes the pulse width modulation and capacitor voltage balancing method of the hybrid multilevel converter. The method adopted in this paper allows operation of the hybrid multilevel converter independent of load power factor.

The dc link of the hybrid multilevel converter can be treated as three independent boost converters with variable capacitor and shared inductor L_{dc}. Therefore, in steady-state the total voltage across the chain link capacitors of the three limbs is:

$$V_d = V_{dc}/m \qquad (1)$$

If the voltage across the chain link capacitors of each limb is V_{dx}, the ac voltages v_{a1}, v_{b1}, v_{c1} shown in Fig. 1a are expressed as:

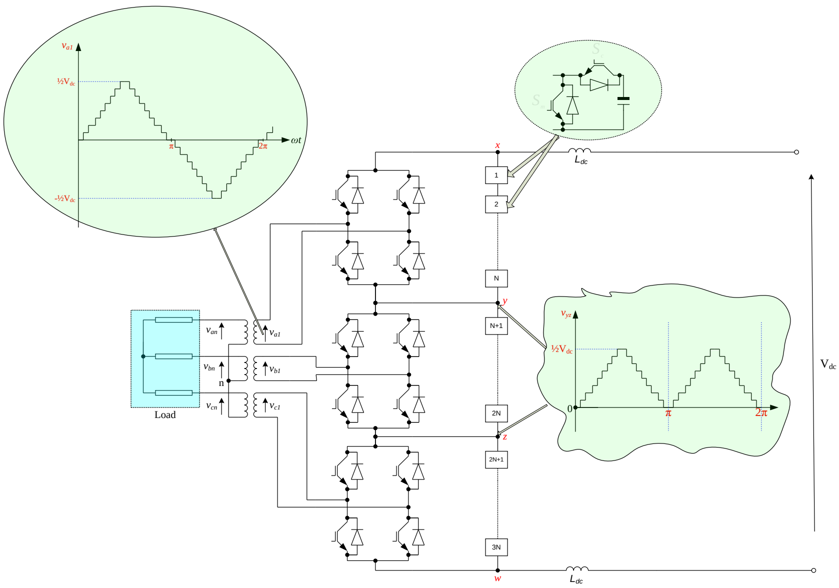
$$v_{a1} = mV_{dx}\sin\omega t,\ v_{b1} = mV_{dx}\sin(\omega t - \tfrac{2}{3}\pi),\ \text{and } v_{c1} = mV_{dx}\sin(\omega t - \tfrac{4}{3}\pi)$$

where m is the modulation index and V_{dc} is the total dc link voltage. During converter operation, the voltage across each limb is modulated between 0 and V_{dx1} such that the following condition must be satisfied:

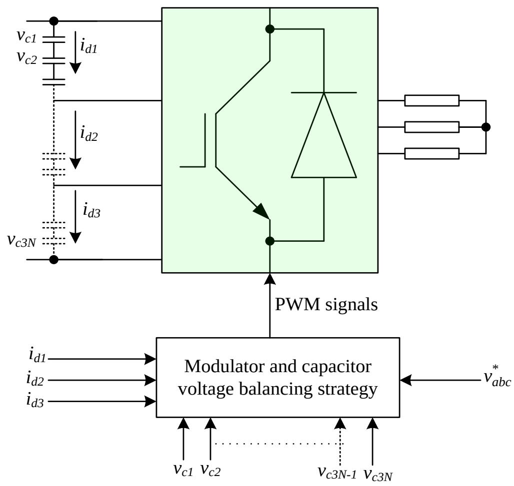
$$\max(|v_{a1}| + |v_{b1}| + |v_{c1}|) = \tfrac{1}{m}V_{dc} \qquad (2)$$

This implies that $V_{dx}=½V_d$.

Equation (1) confirms that the total voltage across the chain link capacitors of the three limbs is modulation index dependent. Lower modulation indices mean higher voltage stress across the chain link capacitors and switching devices. Varying modulation index does not alter the fundamental voltage magnitude. Such a feature is not desirable in applications such as HVDC and FACTS devices where reactive power control is achieved by adjusting the voltage magnitude at the converter terminal with respect to grid voltage. In reference [3] reactive power control of the hybrid multilevel converter is achieved by adjusting the magnitude of the triplen harmonic injected in order to improve dc link utilization.

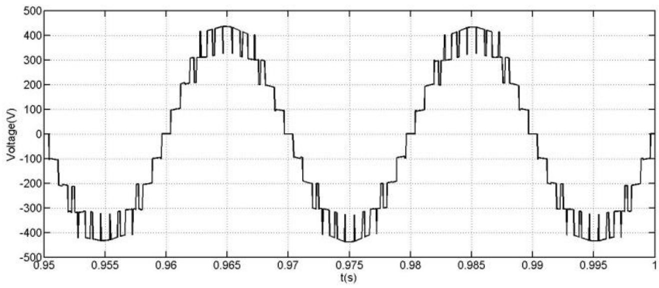


(a) Three-phase hybrid multilevel converter for medium and high voltage applications

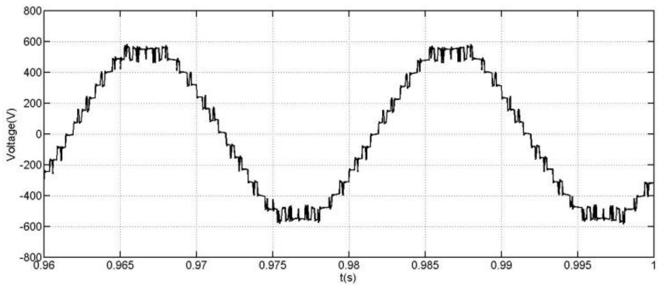


(b) Pulse width modulation and capacitor voltage balancing method

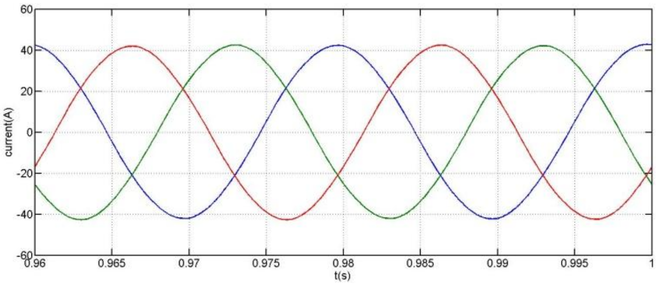
Fig. 1: Hybrid multilevel converter and block diagram depicting its pulse width modulation and capacitor voltage balancing method



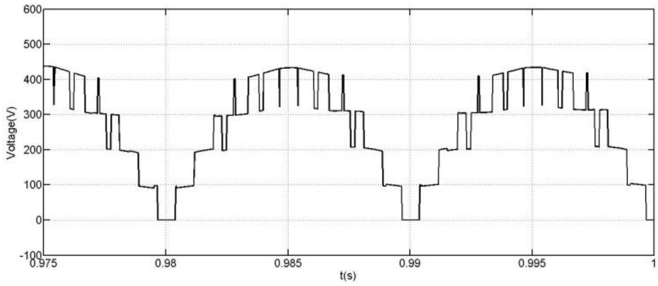
a) Phase voltage at converter side (va1)



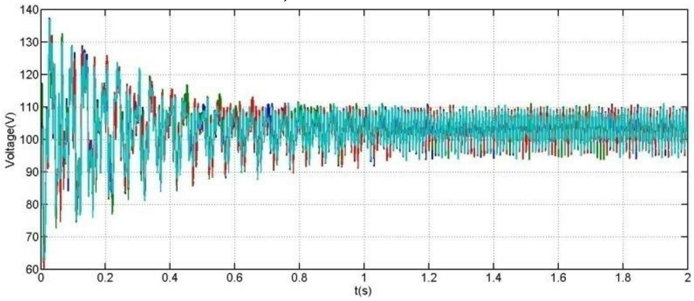
b) Line voltage at the load side



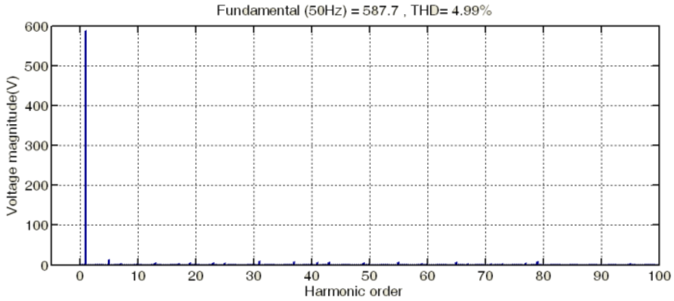
c) Load currents



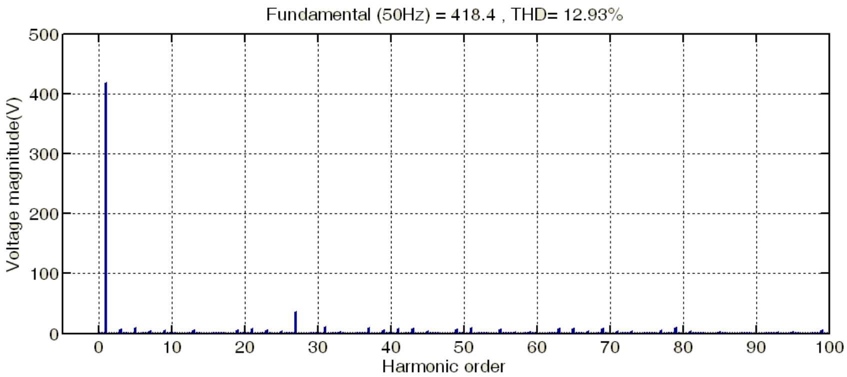
d) Voltage across the chain links of the top limb



e) Voltage across the four chain link capacitors of the top limb

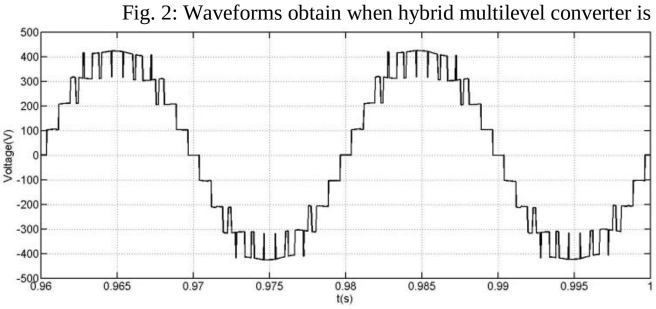


f) Line voltage spectrum

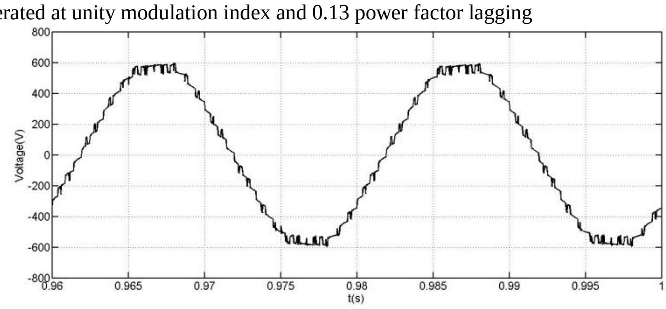


g) Phase voltage spectrum

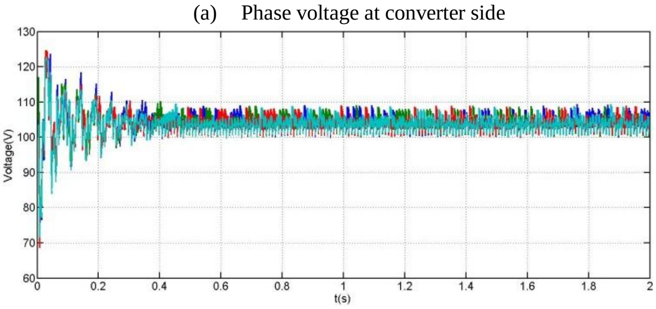
Fig. 2: Waveforms obtain when hybrid multilevel converter is operated at unity modulation index and 0.13 power factor lagging



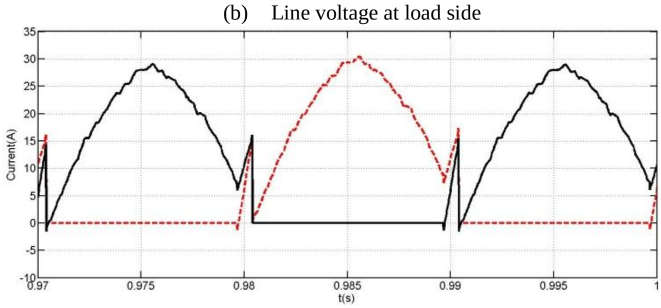
(a) Phase voltage at converter side



(b) Line voltage at load side

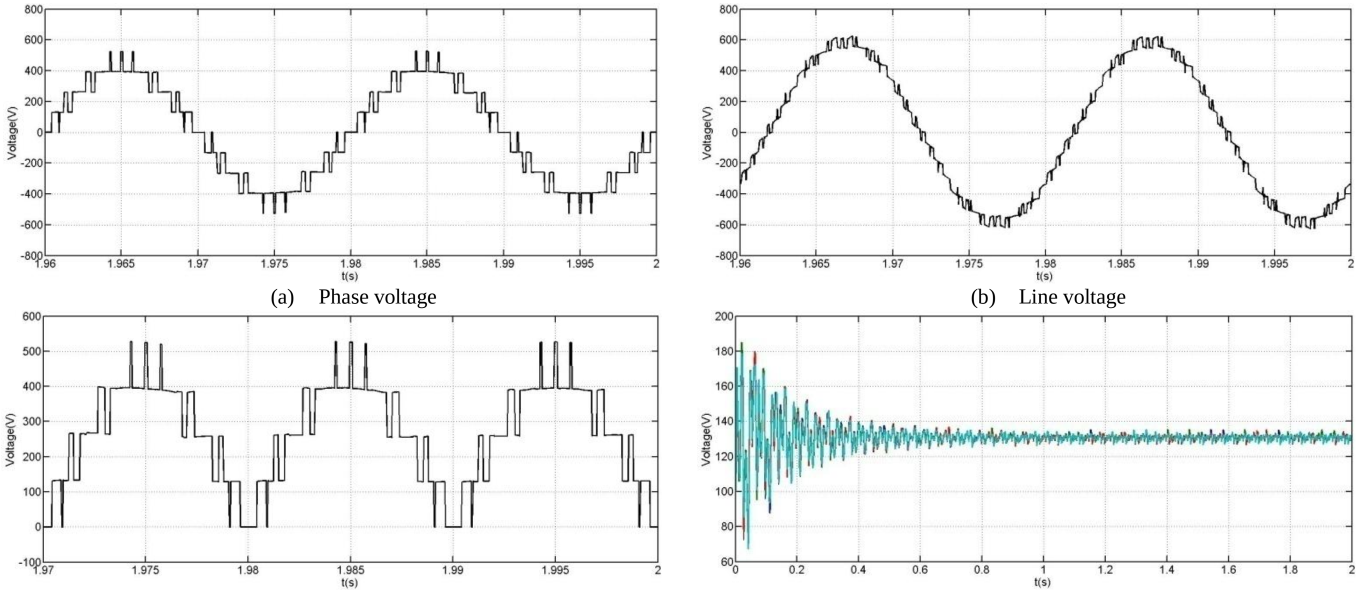


(c) Voltage across the four chain link capacitors of the top limb



(d) Currents in the complementary switches of the high voltage stage (H-bridge)

Fig. 3: Waveforms obtain when hybrid multilevel converter is operated at unity modulation index and unity power factor



(a) Phase voltage (b) Line voltage

(c) Voltage across the chain links of top limb (d) Voltage across the chain link capacitors of the top limb

Fig. 4; Waveforms obtain when hybrid multilevel converter with four chain links per limb is operated at unity power factor and 0.8 modulation index

III. SIMULATIONS

Fig. 2 shows the results obtained when the hybrid multilevel converter with four chain links per limb is operated at different load power factors. The system parameters are 4mF chain link capacitor, 2mH dc link inductor, and the converter transformer is rated at 100KVA 600/440V. The hybrid multilevel converter with only four chain link capacitors per limb generates nine-voltage levels per phase and nineteen voltage levels in the line voltage (Figs. 2a and 2b). This may result in significant improvement in output waveform quality, reduced *dv/dt*, and small converter footprint. Fig. 2c shows the load current is sinusoidal. Fig. 2d shows a step approximation of the rectified sinusoidal voltage across the upper limb. The switching of one voltage level at each instant is maintained at the chain links. This ensures low switching loss and *dv/dt* will be experienced by converter transformer. Fig. 2e shows that voltage balancing of the chain link capacitors is maintained when the converter delivers large reactive power, without the need for triplen harmonic injection as claimed in reference [3]. Spectrums of line and phase voltages shown in Figs. 2e and 2f. Figs. 2e and 2f show that hybrid multilevel converter generates output voltages with extremely low harmonic content with a fewer number of chain links.

Fig. 3 shows the results obtained when the hybrid multilevel converter is operated at unity power factor and unity modulation index. These results confirm the ability of the hybrid multilevel converter to operate independent of load power factor. Fig. 3d confirms fundamental frequency operation of the high-voltage stage (H-bridge).

The results in Fig. 4 are obtained when the hybrid multilevel converter is operated with 0.8 modulation and unity power factor. The voltages across the chain link capacitors is maintained approximately at $\frac{1}{2mN}V_{dc}$ which is 125V. Figs. 4a and 4b show the phase and line voltage, and Fig. 4c shows the voltage waveform across the upper limb. The voltage at the input of the upper H-bridge is modulated between 500V and 0. This is confirmed by the voltage waveforms across the chain link capacitors in Fig. 4c.

The main drawback of the approach used in this paper is that it allows the voltage across the chain capacitors to vary significantly with variation in modulation index. This may result in the switching devices within the chain links experiencing high voltage stresses. As a result, the chain link switching devices must be rated to tolerate a large variation in capacitor voltages.

IV. CONCLUSIONS

This paper investigated the viability of a hybrid multilevel converter for medium and high voltage application. It has been demonstrated that this converter, with passive front end, may not suitable for applications that required variable ac voltage. However, it can be used with an active front end in back-to-back arrangement to achieve variable ac voltages provided the dc link voltage is maintained constant. The distinct features of the hybrid multilevel converter demonstrated in this paper are:

- Requires fewer capacitors and devices (small footprint and low conversion losses).
- Generates a large number of levels with fewer cells; this may eliminate ac filters.
- Operation independent of load power factor, making it suitable for a wide range of applications.

- Inability to generate variable ac voltage may limit the applications of hybrid multilevel converters. Therefore, its ability to operate with a weak ac system without appropriate ac voltage control capability is in doubt.
- Modular structure

V. References

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