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Loss Comparison of Different Nine-Switch and Twelve-Switch Energy Conversion Systems

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***Abstract*— Nine-switch converter is a recently proposed reduced-switch equivalence of the twelve-switch back-to-back converter. The usual expectation is thus for the nine-switch converter to face some switching constraints and hence performance tradeoffs. However, this might not always be the case with an answer only available after performing a thorough analysis. For that, it is the intention now to compare the nine-switch and twelve-switch converters when they are used in ac-ac, ac-dc, dc-ac or dc-dc energy conversion systems. Their losses will be compared to identify when the nine-switch converter will have an advantage or face only a slight constraint, which can hence better justify its usage to save switches. Simulation results are presented, while experimental loss measurements are presently ongoing.**

I. Introduction

As technology evolved, industry has constantly been searching for ways to reduce the sizes and costs of power converters, while improving their reliabilities. That leads to the development of many new converters and their modulation methods, which so far, has focused on improving a few topological or performance features. One of the popularly pursued features is to reduce the number of components needed for implementing the converters. For passive components, the commonly mentioned example will probably be the ac-ac matrix converters, where no bulky dc-link capacitor is needed [1]. Matrix converters are thus referred to as “all-semiconductor” even though a clamping capacitor is still needed in practice. Development in matrix converters has subsequently been progressed to the indirect type [2], where a fictitious dc-link has been introduced, but no large dc-link capacitor is again used. This progress allows active switches to be reduced, leading to those sparse matrix converters proposed in [3].

Indeed, reducing of active switches is helpful since it also removes some accompanying gate circuits, and hence minimizes the chances of short-circuit and open-circuit failures caused by electromagnetic interferences. Many more reduced-switch converters are thus proposed over the years with most having the voltage-source characteristics. A common example is the B4 converter [5], which uses four switches to form two phase-legs. The third phase-leg is then drawn out from the middle of a split dc-link capacitor. The B4 converter thus saves two switches as compared to the standard six-switch converter. The same reduction of switches can be performed when two six-switch bridges are connected back-to-back to form an ac-dc-ac converter. An example, which saves two switches, is discussed in [4], where the five-leg converter is proposed. Based on slightly different topological principles, a more recent example can be found almost simultaneously in [5] and [6], where the nine-switch converter is proposed to save three switches. The nine-switch converter has since been tested for single and dual motor drives [5][7], uninterruptable power supplies [6] and unified power quality conditioners [8] with its performance noted to be not always satisfactory for some of them [7]. This is no doubt linked to performance constraints introduced by its reduced switch count, which are also experienced by other reduced-switch topologies. It is hence important to study the nine-switch converter with more details before appropriate application areas can be identified for it to benefit from its reduced switch feature, while not being burdened by its performance constraints. For that, loss generation of the nine-switch converter is now compared with its twelve-switch back-to-back equivalence.

II. Opperational Principle of Nine-Switch Converter

As seen in Fig. 1, the nine-switch converter is formed by three phase-legs with three switches each. It therefore saves three switches (or 25% depending on how many phase-legs are required), as compared to its twelve-switch equivalence shown in Fig. 2. Using fewer switches however introduces a constraint to the nine-switch converter, as demonstrated in Table I, where the fourth state of $V_{A\_UP} = 0$ and $V_{A\_DN} = V_{dc}$ cannot be generated. In terms of modulation, it means the sinusoidal reference used for the upper terminal must always be placed above that of the lower terminal, as demonstrated in Fig. 3. Phase-shift between the two references is therefore limited if they have the same frequency and their amplitudes summed to be greater than that of the triangular carrier. On the other hand, if their frequencies are different, their total amplitude must always be smaller than the carrier amplitude. These constraints simply mean that application of the nine-

TABLE I. OPERATING STATES OF NINE-SWITCH CONVERTER

Switch State	Voltage
S_{A1} = S_{A2} = ON and S_{A3} = OFF	$V_{A\_UP} = V_{dc}$ and $V_{A\_DN} = V_{dc}$
S_{A1} = S_{A3} = ON and S_{A2} = OFF	$V_{A\_UP} = V_{dc}$ and $V_{A\_DN} = 0$
S_{A2} = S_{A3} = ON and S_{A1} = OFF	$V_{A\_UP} = 0$ and $V_{A\_DN} = 0$
Fourth combination of $V_{A\_UP} = 0$ and $V_{A\_DN} = V_{dc}$ cannot be realized.	

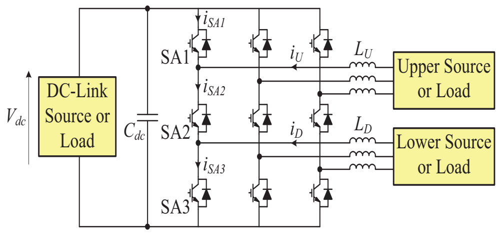


Fig. 1. Nine-switch converter

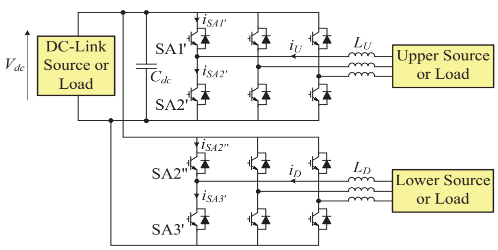


Fig. 2. Twelve-switch back-to-back converter

switch converter should be studied carefully in the following sections, before real saving can be gained from its fewer switches.

III. LOSS COMPUTATION

Losses in the switches include conduction and switching losses, which can be computed using models describing specific switches or the generic model found in [9]. Since the aim here is to show the relative merits between the two converters without biasing of specific switches, the generic model is deemed as appropriate, whose expressions are given as follows.

A. Conduction Losses

Conduction losses produced by the three switches in a phase-leg of the nine-switch converter can be computed using (1) based on the current notations used in Fig. 1 and the instantaneous current expressions shown in Fig. 4 for half a carrier period. The same computation can be repeated for the other two phases.

$$P_{Con_{SA1}} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left(\left(k_1 V_{Tran_{On}} + (1-k_1)V_{Diode_{On}}\right)|i_U|(T-T_1-T_2) + \left(k_3 V_{Tran_{On}} + (1-k_3)V_{Diode_{On}}\right)|i_U+i_D|T_2\right)\right\}_\epsilon$$

$$P_{Con_{SA2}} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left(\left((1-k_1)V_{Tran_{On}} + k_1 V_{Diode_{On}}\right)|i_U|T_1 + \left(k_2 V_{Tran_{On}} + (1-k_2)V_{Diode_{On}}\right)|i_D|T_2\right)\right\}_\epsilon$$

$$P_{Con_{SA3}} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left(\left((1-k_3)V_{Tran_{On}} + k_3 V_{Diode_{On}}\right)|i_U+i_D|T_1 + \left((1-k_2)V_{Tran_{On}} + k_2 V_{Diode_{On}}\right)|i_D|(T-T_1-T_2)\right)\right\}_\epsilon$$

$$k_1 = \begin{cases}1, & i_U \le 0\\ 0, & i_U > 0\end{cases},\ k_2 = \begin{cases}1, & i_D \le 0\\ 0, & i_D > 0\end{cases},\ k_3 = \begin{cases}1, & i_U + i_D \le 0\\ 0, & i_U + i_D > 0\end{cases} \tag{1}$$

where V_{Tran_On} and V_{Diode_On} are respectively the ON voltages of the transistor and diode in a switch. Corresponding expressions for switches of the equivalent twelve-switch converter can also be written as (2) based on the notations used in Fig. 2 and current expressions shown in Fig. 4:

$$P_{Con\_SA1'} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left(k_1 V_{Tran\_On} + (1-k_1)V_{Diode\_On}\right)|i_U|(T-T_1')\right\}_\epsilon$$

$$P_{Con\_SA2'} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left((1-k_1)V_{Tran\_On} + k_1 V_{Diode\_On}\right)|i_U|T_1'\right\}_\epsilon$$

$$P_{Con\_SA2''} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left(k_2 V_{Tran\_On} + (1-k_2)V_{Diode\_On}\right)|i_D|T_2'\right\}_\epsilon$$

$$P_{Con\_SA3'} = \sum_{\epsilon=1\to f_{SW}} \left\{2\left((1-k_2)V_{Tran\_On} + k_2 V_{Diode\_On}\right)|i_D|(T-T_2')\right\}_\epsilon \tag{2}$$

B. Switching Losses

The switching losses of the nine-switch converter can be computed using (3). Assuming that the switching frequency is high and current values in a switching period are nearly constant, expressions for computing switching losses of the

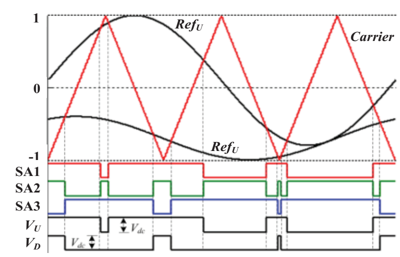


Fig. 3. Modulation of nine-switch converter

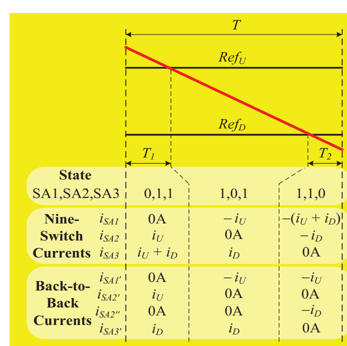


Fig. 4. Instantaneous switch current expressions

equivalent twelve-switch converter are given in (4).

$$P_{SW\_SA1} = \sum_{\epsilon=1\to f_{SW}} \left\{\frac{1}{2}V_{dc}|i_U|\left(k_1\left(t_{Tran\_R} + t_{Tran\_F}\right) + (1-k_1)t_{Diode\_F}\right)\right\}_\epsilon$$

$$P_{SW\_SA2} = \sum_{\epsilon=1\to f_{SW}} \left\{\frac{1}{2}V_{dc}|i_U|\left((1-k_1)\left(t_{Tran_R} + t_{Tran_F}\right) + k_1 t_{Diode_F}\right) + \frac{1}{2}V_{dc}|i_D|\left(k_2\left(t_{Tran\_R} + t_{Tran\_F}\right) + (1-k_2)t_{Diode\_F}\right)\right\}_\epsilon$$

$$P_{SW\_SA3} = \sum_{\epsilon=1\to f_{SW}} \left\{\frac{1}{2}V_{dc}|i_D|\left((1-k_2)\left(t_{Tran\_R} + t_{Tran\_F}\right) + k_2 t_{Diode\_F}\right)\right\}_\epsilon \quad (3)$$

$$P_{SW\_SA1'} \approx \frac{V'_{dc}}{V_{dc}} P_{SW\_SA1},$$
$$P_{SW\_SA2'} \approx \frac{V'_{dc}}{V_{dc}} \times First\ term\ of\ P_{SW\_SA2},$$
$$P_{SW\_SA2''} \approx \frac{V'_{dc}}{V_{dc}} \times Second\ term\ of\ P_{SW_{SA2}} \Rightarrow$$
$$P_{SW\_SA2'} + P_{SW\_SA2''} \approx P_{SW\_SA2},$$
$$P_{SW\_SA3'} \approx \frac{V'_{dc}}{V_{dc}} P_{SW\_SA3} \quad (4)$$

C. Differences in Losses

To simplify the expressions for easier understanding, switching instants of the two converters are assumed to be the same. That means $T_1 \approx T'_1$ and $T_2 \approx T'_2$, which is approximately the case at high nominal modulation conditions. Differences in conduction losses for the two converters can hence be written as (5).

$$P_{Con\_SA1} = P_{Con\_SA1} - P_{Con\_SA1'} \approx \sum_{\epsilon=1\to f_{SW}} \left\{2T_2\left(\left(k_3 V_{Tran\_On} + (1-k_3)V_{Diode\_On}\right)|i_U + i_D| - \left(k_1 V_{Tran\_On} + (1-k_1)V_{Diode\_On}\right)|i_U|\right)\right\}_\epsilon$$

$$\Delta P_{Con\_SA2} = P_{Con\_SA2} - P_{Con'_{SA2}} - P_{Con\_SA2''} \approx 0$$

$$\Delta P_{Con\_SA3} = P_{Con\_SA3} - P_{Con\_SA3'} = \sum_{\epsilon=1\to f_{SW}} \left\{2T_1\left(\left((1-k_3)V_{Tran\_On} + k_3 V_{Diode\_On}\right)|i_U + i_D| - \left((1-k_2)V_{Tran\_On} + k_2 V_{Diode\_On}\right)|i_D|\right)\right\}_\epsilon \quad (5)$$

Certainly not the case in practice, but for simplifying the analysis further, V_{Tran_On} and V_{Diode_On} are assumed to be equal ($= V_{On}$). Equation (5) then becomes (6).

$$\Delta P_{Con\_SA1} \approx \sum_{\epsilon=1\to f_{SW}} \{2V_{On}T_2(|i_U + i_D| - |i_U|)\}_\epsilon$$
$$\Delta P_{Con\_SA2} \approx 0$$
$$\Delta P_{Con\_SA3} \approx \sum_{\epsilon=1\to f_{SW}} \{2V_{On}T_1(|i_U + i_D| - |i_D|)\}_\epsilon \quad (6)$$

It is thus clear that the differences in conduction losses between the two converters are solely dependent on their relative current magnitudes and time durations (T_1 and T_2) in each switching period. Corresponding differences in switching losses can also be determined as (7), from which it can be seen that differences in losses can be minimized by lowering the dc-link voltage of the nine-switch converter, where possible.

$$\Delta P_{SW\_SA1} = P_{SW\_SA1} - P_{SW\_SA1'} \approx \left(1 - \frac{V'_{dc}}{V_{dc}}\right) P_{SW\_SA1}$$
$$\Delta P_{SW\_SA2} = P_{SW\_SA2} - \left(P_{SW\_SA2'} + P_{SW\_SA2''}\right) = \left(1 - \frac{V'_{dc}}{V_{dc}}\right) P_{SW\_SA2}$$
$$\Delta P_{SW\_SA3} = P_{SW\_SA3} - P_{SW\_SA3'} \approx \left(1 - \frac{V'_{dc}}{V_{dc}}\right) P_{SW\_SA3} \quad (7)$$

Equations (6) and (7) can subsequently be used for analyzing energy conversion systems to be discussed next.

IV. Same Frequency Operation (AC-AC and DC-DC)

Same frequency operation includes both ac-ac and dc-dc energy conversion systems with the latter being a simplified case of the former at zero frequency. Modulating references used for operating them can hence be summarized as:

$$Ref_U = M_U cos(\omega t) + M_{oU} + M_{Tri\_U},$$
$$Ref_D = M_D cos(\omega t + \varphi) - M_{oD} + M_{Tri\_D} \quad (8)$$

where $0 \le M_U \le 1$ and $0 \le M_D \le 1$ are the modulation ratios, M_{Tri_U} and M_{Tri_D} are triplen offsets added to gain a 15% extension of the linear modulation range, and M_{oU} and M_{oD} are constant offsets added to ensure that Ref_U is always above Ref_D. Applying the first and third expressions of (6) to this operating mode then shows that a reduction in conduction losses can always be achieved by the nine-switch converter if (9) is satisfied, regardless of the values of T_1 and T_2.

$$|i_U + i_D| \le |i_U| \quad \text{and} \quad |i_U + i_D| \le |i_D| \quad (9)$$

For the case of the converter supplying sinusoidal currents at the fundamental frequency, (9) can further be expressed as (10).

$$\begin{cases} I_U^2 + I_D^2 - 2I_D I_U cos(180° - \theta) \le I_D^2 & if\ I_D \le I_U \\ I_U^2 + I_D^2 - 2I_D I_U cos(180° - \theta) \le I_U^2 & if\ I_U \le I_D \end{cases}$$

where $i_U = I_U cos(\omega t + \theta_U)$ and $i_D = I_D cos(\omega t + \theta_D)$

$$\Rightarrow \begin{cases} |I_U/I_D| \le 2cos(180° - \theta) & if\ I_D \le I_U \\ |I_D/I_U| \le 2cos(180° - \theta) & if\ I_U \le I_D \end{cases}, \theta = \theta_U - \theta_D \quad (10)$$

For the ideal case of $\theta = 180°$ and $|i_U| = |i_D|$ (*one terminal absorbing and the other supplying power*), currents through SA1 and SA3 of the nine-switch converter will be cancelled, hence generating zero conduction losses during T_1 and T_2. Switching losses of the nine-switch converter is also not increased under same frequency operation, since its dc-link voltage can remain the same as its twelve-switch equivalence. This can clearly be seen from (7) after setting $V_{dc} = V'_{dc}$.

V. Different Frequency Operation (AC-DC, DC-AC and AC-AC)

Different frequency operation includes ac-dc, dc-ac and ac-ac conversion, which will be analyzed sequentially as follows.

A. AC-DC Conversion

Modulating references used for ac-dc conversion are summarized in (11), from which expressions for T_1 and T_2 are also derived. Also included in (11) are the ac and dc currents that are assumed to flow into the converter.

$$
\begin{aligned}
&Ref_U = M_U cos(\omega t) + M_{oU} + M_{Tri\_U},\\
&Ref_D = -M_{oD},\\
&T_1 = 0.5T(1 - Ref_U),\ \ T_2 = 0.5T(1 + Ref_D)\\
&i_U = I_U cos(\omega t + \theta_U),\ \ i_D = I_D
\end{aligned}
\tag{11}
$$

Clearly, T_1 is time-varying, while T_2 is fixed and should be kept small to keep V_{dc} of the nine-switch converter closer to V'_{dc} of the twelve-switch converter in order to minimize the switching loss differences in (7) [11]. From (6), the sum of conduction loss differences for the nine-switch converter can then be written as (12), where the second and third terms are noted to have only a single variable for summation. They are hence "uncontrollable". Unlike them, the first term in (12) can be lowered on average by making the maximum value of $(T_1 + T_2)$ coinciding with the minimum value of $|i_U + I_D|$, and vice versa (anti-phase). Ideally, that can be ensured by having Ref_U in phase with i_U and $I_U \approx I_D$ (*both terminals supplying or absorbing power*).

$$
\Delta P_{Con_{SA}} = \sum_{X=1,2,3} \Delta P_{Con_{SAX}} \approx 2V_{On}\big[\sum_{\epsilon=1\to f_{SW}}\{(T_1 + T_2)|i_U + I_D|\}_\epsilon - I_D \sum_{\epsilon=1\to f_{SW}}\{T_1\}_\epsilon - T_2 \sum_{\epsilon=1\to f_{SW}}\{|i_U|\}_\epsilon\big]
\tag{12}
$$

B. DC-AC Conversion

The recommended operating conditions for dc-ac conversion are different from those for ac-dc conversion, although it sounds like a simple interchange in ac-dc conversion. Modulating reference for dc-ac conversion as well as currents flowing in the converter are summarized in (13) with the same expression for T_1 and T_2 like in (11). Here, T_2 is time-varying and T_1 is fixed and should be kept small to minimize the switching loss differences in (7).

$$
\begin{aligned}
&Ref_U = M_{oU},\\
&Ref_D = M_D cos(\omega t) - M_{oU} + M_{Tri\_D},\\
&i_U = I_U,\ i_D = I_D\ cos(\omega t + \theta_D)
\end{aligned}
\tag{13}
$$

Similarly to ac-dc conversion, the sum of conduction loss differences for the nine-switch converter for dc-ac conversion can be written as (14)

$$
\Delta P_{Con_{SA}} = \sum_{X=1,2,3} \Delta P_{Con_{SAX}} \approx 2V_{On}\big[\sum_{\epsilon=1\to f_{SW}}\{(T_1 + T_2)|I_U + i_D|\}_\epsilon - I_U \sum_{\epsilon=1\to f_{SW}}\{T_2\}_\epsilon - T_1 \sum_{\epsilon=1\to f_{SW}}\{|i_D|\}_\epsilon\big]
\tag{14}
$$

Assuming the upper terminal in nine-switch converter is drawing dc power with $i_U = I_U > 0$ and the lower terminal is supplying ac power with i_D phase shifted with Ref_D by 180°. With $i_D > 0$ averaging the first term in (14) leads to increase for a shorter T_2, since Ref_D is closer to triangular wave. In contrary, when $i_U < 0$, averaging of the first term in (14) leads to decrease for a longer T_2, since Ref_D has more distance to triangular wave. Therefore, since the second and third terms in (14) are uncontrollable, the minimization of conduction power loss can be achieved by choosing i_U as positive and i_D as negative or vice versa with peak of $|i_D| \approx |i_U|$. This means one terminal must be supplying power, while the other absorbing power.

C. AC-AC Conversion

For ac-ac conversion, one can assume that the upper terminal current frequency is extremely higher than the lower terminal, $\omega_U \gg \omega_D$. Lower terminal current can be approximated as dc in upper fundamental frequency. Hence, like to section V.B, the average conduction loss can be minimized by Ref_U in phase with i_U, positive i_D and $I_U \approx I_D$. However, the average conduction loss will be increased when i_D becomes negative. Consequently, the earlier loss minimization will be cancelled leading to no distinguished advantage for nine-switch converter in ac-ac conversion. Therefore, it is recommended to keep the $I_U \approx I_D$.

VI. SIMULATION EXAMPLES

For verification, the understanding and prediction tools developed were applied to identify conditions during which the nine-switch converter will have an advantage over its twelve-switch equivalence. The conditions chosen for testing are listed in Table II. Upper and lower terminal currents for ac-ac nine-switch and twelve-switch systems operating at a single common frequency followed by an ac-dc system operating at different frequencies are shown as examples in Fig.5 and Fig.6. The terminal currents verify the same operation of nine-switch system in substitution of twelve-switch system considering its less switch counts.

In addition, the results obtained for individual switch power losses are shown in Fig. 7. It is observed for all cases, switching loss difference is negligible by setting of $V_{dc} \approx V'_{dc}$. In ac-ac conversion with same frequency and dc-dc conversion, it is clear in Fig 7.a and 7.d that (9) is met and the reduction in conduction loss is achieved for both conversion systems. For ac-dc conversion, according to discussion in section V.A, both terminals should absorb or supply power, and the minus sign for currents in Table II means both terminals absorb power. Hence, the power saving is achieved as shown in Fig 7.B. In dc-ac conversion, as shown in Table II, in nine-switch converter one terminal supplies power and the other terminal draws power. Hence, the advantage in reduction of conduction loss can be verified in Fig. 7.c.

Fig. 8 presents an efficient verification of the concepts developed. To be more precise, Fig. 8 shows the total losses obtained for the different energy conversion systems. It uniformly shows that the nine-switch converter, despite using fewer switches, can still maintain a performance advantage so long as it is applied appropriately based on the understanding gained in this paper.

VII. CONCLUSION

In this paper, loss generation of the nine-switch converter is compared with its twelve-switch equivalence for different types of energy conversion systems. The purpose is to identify application areas where the nine-switch converter can have a loss advantage despite its reduced-switch feature. For

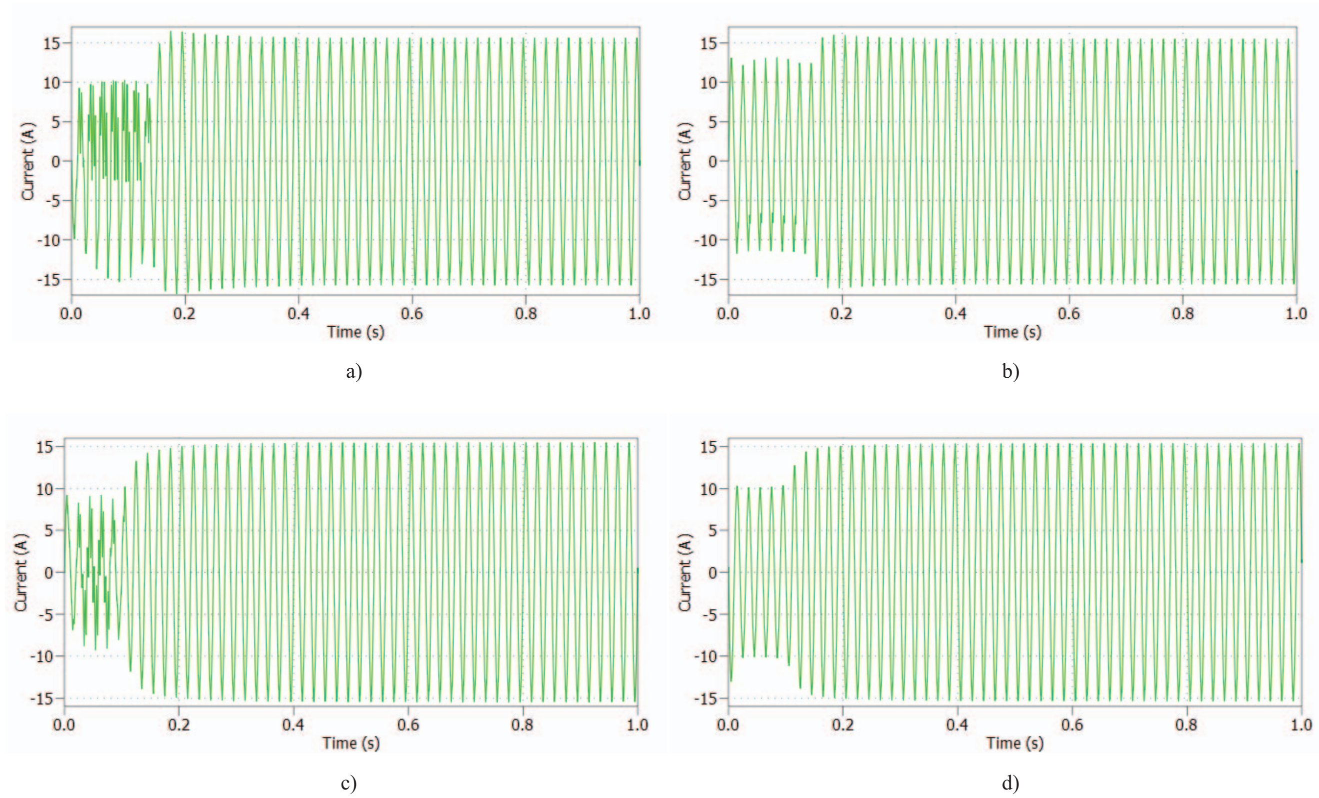


Fig. 5. Terminal currents of ac-ac nine-switch system a) upper terminal, b) lower terminal and twelve-switch system c) upper terminal d) lower terminal

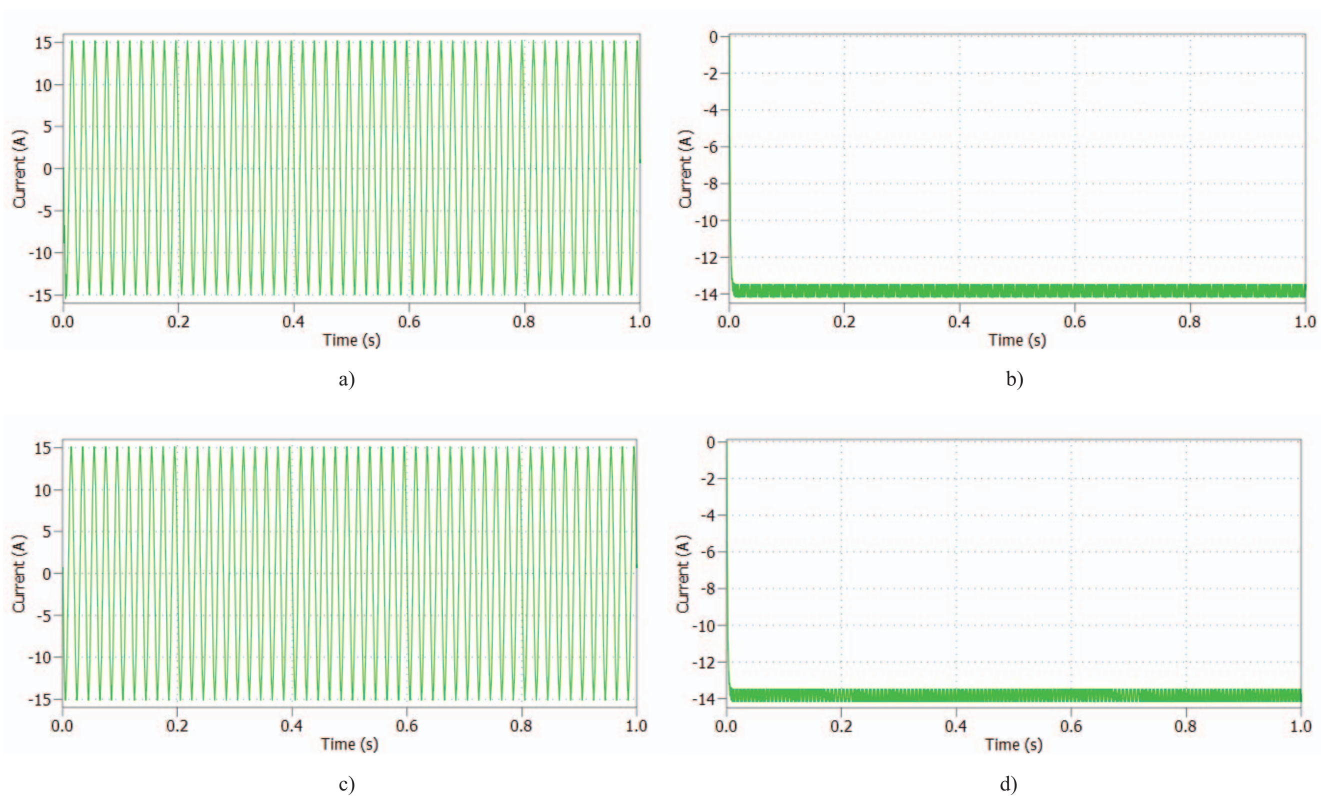
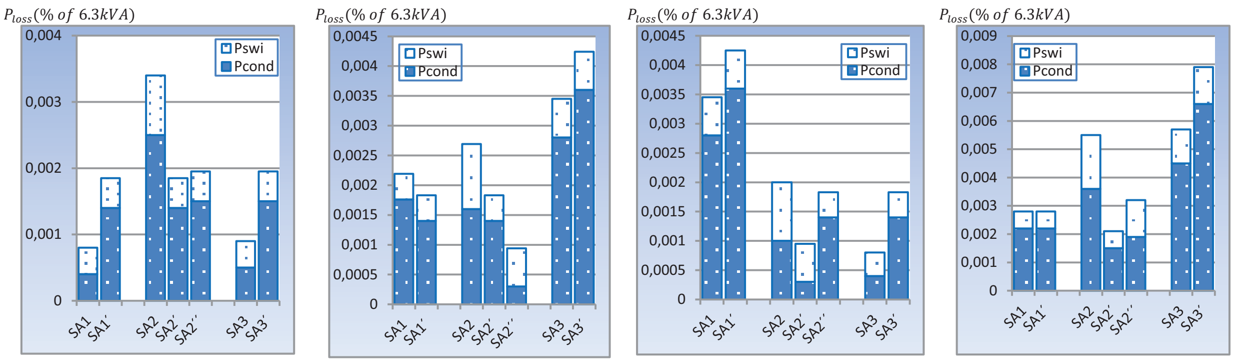


Fig. 6. Terminal currents of ac-dc nine-switch system a) upper terminal, b) lower terminal and twelve-switch system c) upper terminal d) lower terminal

TABLE II. PARAMETERS USED FOR TESTING ('+' MEANS ABOSORBING AND '-' MEANS SUPPLYING CURRENT BY THE CONVERTER)

Type	Nine-Switch Converter	Twelve-Switch Converter
AC-AC	$I_U = +11.27$ A, $I_D = -10.75$ A, $\theta = 5°$ $M_U = 0.82$, $M_{oU} = 0.1$ $M_D = 0.8$, $M_{oD} = -0.15$, $\theta_{RefU} - \theta_{RefD} = 12.6°$	$I_U = +10.49$ A, $I_D = -10.35$ A, $\theta = 5°$ $M_U = 0.82$, $M_{oU} = 0.1$ $M_D = 0.8$, $M_{oD} = -0.15$, $\theta_{RefU} - \theta_{RefD} = 12.6°$
AC-DC	$I_U = -10.92$ A, $I_D = -13.82$ A, $M_U = 0.9$, $M_{oU} = 0.1$, $M_D = -0.85$	$I_U = -10.25$ A, $I_D = -13.82$ A, $M_U = 0.9$, $M_{oU} = 0.1$, $M_D = -0.85$
DC-AC	$I_U = +13.96$ A, $I_D = -13.07$ A, $M_U = 0.85$, $M_D = 0.9$, $M_{oD} = -0.08$	$I_U = +13.96$ A, $I_D = -13.12$ A, $M_U = 0.85$, $M_D = 0.9$, $M_{oD} = -0.08$
DC-DC	$I_U = -10.24$ A, $I_D = +11.16$ A, $M_U = 0.1$, $M_D = -0.5$	$I_U = -10.76$ A, $I_D = +11.48$ A, $M_U = 0.1$, $M_D = -0.5$



a) ac-ac b) ac-dc c) dc-ac d) dc-dc

Fig. 7. Individual switch power losses of different nine-switch and twelve-switch energy conversion systems

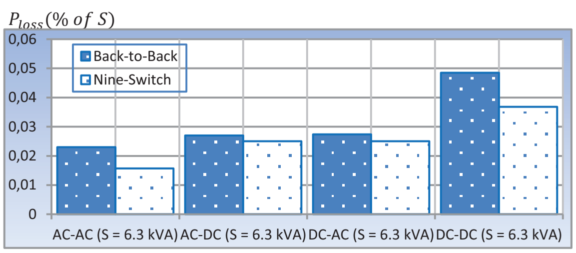


Fig. 8. Total power losses of different energy systems.

that, it is identified that the nine-switch converter will have an advantage when used for ac-ac, dc-ac and dc-dc energy conversion, if one of its terminals is supplying power while the other absorbs power. The converter also has an advantage when used for ac-dc conversion, but both its terminals must now either supply or absorb power. In all cases though, performance of the converter will be optimized if its terminal currents are comparable in magnitude.

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