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Published in:
Proceedings of the 39th Annual Conference of IEEE Industrial Electronics Society, IECON 2013

DOI (link to publication from Publisher):
10.1109/IECON.2013.6699229

Publication date:
2013

Document Version
Early version, also known as pre-print

Evaluation of Switch Currents in Nine-Switch Energy Conversion Systems

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***Abstract*—Converters with reduced switch counts usually face some performance tradeoffs, which make them suitable for some applications but not others. The same applies to the nine-switch converter, which is a reduced-switch version of the back-to-back twelve-switch converter. The nine-switch converter has since been shown to experience a higher voltage stress, which can be lowered in some cases. A corresponding evaluation of its current stress is however lacking, and is hence addressed now by computing its switch currents when used for ac-ac, ac-dc, dc-ac and dc-dc energy conversions. Relevant expressions, application requirements and simulation results are presented for identifying cases, where the nine-switch converter can have an improvement in performance despite its reduced switch count.**

Keywords—Nine-switch converter, twelve-switch converter, back-to-back converter, energy conversion systems

I. Introduction

To date, power converters have found many important routine applications including industrial motor drives, uninterruptible power supplies, electric vehicles and renewable energy systems. Depending on the type of source connected to it, a power converter can be classified as either the voltage-source or current-source type. To illustrate their differences, Fig. 1 shows two elementary three-phase topologies commonly drawn for comparison (only the upper bridge in Fig. 1(a)). Both converters use six switches, but with different orientations. Switches for the voltage-source converter have anti-parallel diodes added to allow for unidirectional voltage blocking and bidirectional current conduction. Switches for the current-source converter, on the other hand, have series diodes added to permit unidirectional current conduction, while blocking voltage in both directions. Commutations of switches for both converters are also different with the voltage-source type demanding for a dead-time to avoid shorting its source, and the current-source type demanding for an overlap delay to avoid opening its source. Based on these and their other closely related operating features, the two classes of converters have commonly been referred to as duals even though they have many physical differences.

Despite their duality, the current-source type is presently lacking behind its voltage-source companion even though it has some advantages for higher power usage. These advantages are however gradually blunted by the extension of standard voltage-source converter to form various multilevel converters. Besides their higher voltage blocking ability, multilevel converters can produce better conditioned waveforms, while retaining attractive features of the voltage-source topology. No doubt, these are performance features that have long been pursued. Another feature that has been of interest too is to reduce the switch count of the voltage-source topology. For that, the most commonly cited example would probably be the B4 converter [1, 2]. Compared with the converter shown in Fig. 1(a) (only the upper bridge), the B4 converter retains four out of six switches for forming two phase-legs. The third phase is then drawn out from the dc-link midpoint formed by two split capacitors. The same removal of phase-legs has also been tried with the twelve-switch converter, which is simply two voltage-source converters connected back-to-back, as shown in Fig. 1(a) [3, 4].

Instead of removing phase-legs, an alternative way of reducing switches has been demonstrated in [5-7] through the development of the nine-switch converter shown in Fig. 2. The nine-switch converter has since been tried with dual ac motor drives, where the doubling of dc-link voltage is a clear disadvantage [5, 6]. The doubled dc-link voltage can however be avoided when using the nine-switch converter as an uninterruptible power supply (UPS) [7] or a universal power quality conditioner (UPQC) [8]. These applications are however limited to ac-ac energy conversion only. The nine-switch converter has subsequently been generalized to include dc energy conversion with a few examples introduced in [9]. Doubling of dc-link voltage for these systems can again be avoided by choosing the right source and load combinations. Usage of the nine-switch converter is therefore not always suitable because of constraints introduced by its reduced switch count.

The above discussion, despite helpful, has focused only on the dc-link voltage increase experienced by the nine-switch converter. Although some effort has been initiated, a comprehensive evaluation of its switch currents is presently lacking, which is addressed now for different ac-ac, ac-dc, dc-ac and dc-dc energy conversion systems. The conclusions drawn can help to better identify suitable applications for the nine-switch converter without being burdened by constraints introduced by its reduced switch characteristic.

II. Operational Principles

Referring to one phase-leg of the nine-switch converter shown in Fig. 2, the voltages produced by it can be summarized in Table I. At any instant, only two switches are turned ON to produce three sets of distinct voltage levels. The

This project is funded by the Center of Reliable Power Electronics (CORPE) in Denmark.

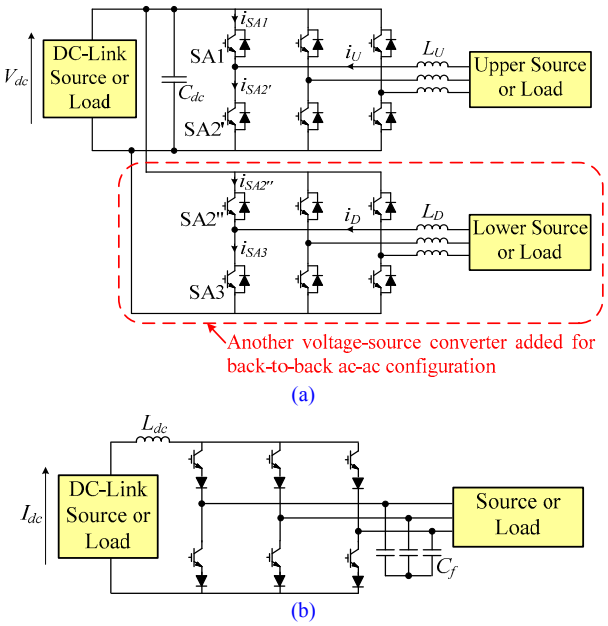

Fig. 1. Illustration of (a) voltage-source and (b) current-source converters.

fourth set, characterized by $V_U = 0$ and $V_D = V_{dc}$, cannot be produced by the phase-leg, which needless to say, is a constraint introduced by the reduced switch characteristic of the nine-switch converter. In terms of modulation, the constraint can be avoided by placing sinusoidal reference Ref_U for the upper phase A terminal above Ref_D for the lower phase A terminal when they are in the same triangular carrier band. This can be ensured by adding a dc offset M_{oU} for shifting Ref_U upwards, and another offset M_{oD} for shifting Ref_D downwards. An illustration showing the eventual placement is given in Fig. 3. A consequence arising from the sharing of carrier band between the references is the doubling of dc-link voltage demanded by the nine-switch converter. The doubled dc-link voltage can fortunately be avoided if the references are of the same frequency and close in phase [6]. It can also be avoided if one reference is much smaller than the other (e.g. $Ref_U \gg Ref_D$) [8]. These findings are however related to voltage, which does not represent the nine-switch converter fully. Its switch currents must also be evaluated, as demonstrated from Section III onwards.

III. Instantaneous Switch Currents

To better compare currents flowing through switches of the nine-switch and twelve-switch converters, the first step is to mark out their equivalent switches. This has been done in Fig. 1(a) and Fig. 2, where the equivalent switches of the two converters have been notated by the same symbols except for three switches. The three switches are SA2 of the nine-switch converter, and SA2' and SA2" of the twelve-switch converter. A one-to-one mapping does not exist for these switches. More correctly, SA2 should be viewed as the merging of SA2' and SA2", which is the reason why the nine-switch converter can save one switch. Instantaneous currents flowing through the switches can then be summarized at the bottom of Fig. 4 for a half carrier period using current notations and directions indicated in Fig. 1(a) and Fig. 2. From the summarized current expressions, the following observations can be noted.

TABLE I. Phase-Leg Voltages 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 $V_{A\_DN} = 0$
Other combinations are not permitted	---

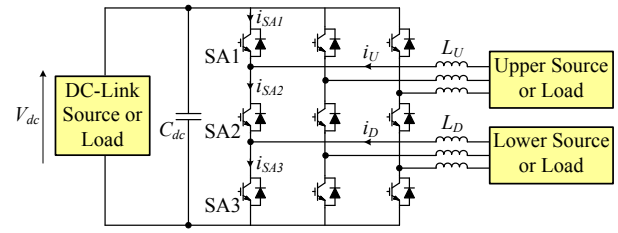

Fig. 2. Illustration of nine-switch voltage-source converter.

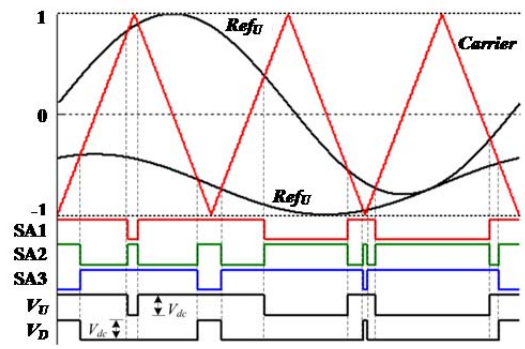

Fig. 3. Modulation of nine-switch converter.

A. Switch SA1

Instantaneous currents flowing through SA1 of the nine-switch and twelve-switch converters are respectively determined as $-(i_U + i_D)$ and $-i_U$ during interval T_2. The former will obviously have a larger magnitude if i_U and i_D are of the same polarity. The reverse is however true if i_U and i_D are of opposite polarities, and magnitude of i_D is smaller than twice that of i_U ($|i_D| < 2|i_U|$, which if not met, will result in $|i_U + i_D| > |i_U|$ even if the two terminal currents have opposite polarities).

B. Switch SA2

Instantaneous current flowing through SA2 of the nine-switch converter is determined as i_U during T_1 and $-i_D$ during T_2. It is thus the sum of i_U flowing through SA2' during T_1 and $-i_D$ flowing through SA2" during T_2 of the twelve-switch converter. Switch SA2 therefore carries no "extra" current.

C. Switch SA3

Switch SA3 of the nine-switch converter carries current $i_U + i_D$ during T_2, which can either be higher or lower than i_D flowing through the same notated switch of the twelve-switch converter. It depends on the polarities and relative magnitudes of i_U and i_D. It is hence similar to SA1.

IV. Application to Energy Conversion Systems

Because of the possible higher currents flowing through switches of the nine-switch converter, its applications must be analyzed carefully before real benefits can be gained from its reduced switch count. For that, the following quantities are

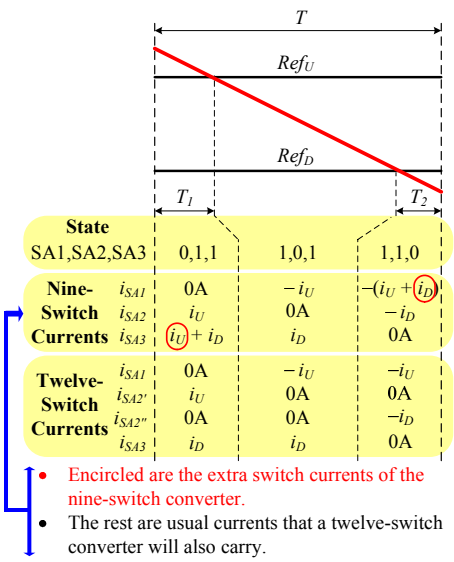

Fig. 4. Instantaneous current expressions in a half-carrier period.

defined before applying them to different energy conversion systems for analysis.

Modulating References and Durations

$$Ref_U = \begin{cases} M_U cos(\omega_U t) + M_{oU} + M_{off,U}, \ if\ ac \\ M_{oU}, \ if\ dc \end{cases}$$

$$Ref_D = \begin{cases} M_D cos(\omega_D t) - M_{oD} + M_{off,D}, \ if\ ac \\ -M_{oD}, \ if\ dc \end{cases}$$

$$T_1 = 0.5T\{1 - Ref_U\}, \ \ T_2 = 0.5T\{1 + Ref_D\} \tag{1}$$

where $0 \le M_U \le 1$ and ω_U are the modulation ratio and angular frequency of the upper terminal, and $0 \le M_D \le 1$ and ω_D are the corresponding values for the lower terminal. Also included in (1) are triplen offsets $M_{off,U}$ and $M_{off,D}$ added to increase the upper and lower linear modulation ranges by 15%.

Terminal Currents

$$i_U = \begin{cases} \sum I_{U,h} cos(h\omega_U t + \varphi_{U,h}), \ if\ ac \\ I_U, \ if\ dc \end{cases}$$

$$i_D = \begin{cases} \sum I_{D,h} cos(h\omega_D t + \varphi_{D,h}), \ if\ ac \\ I_D, \ if\ dc \end{cases} \tag{2}$$

where $h = 1,2,3, \ldots$ is the harmonic order, $I_{U,h}$ and $\varphi_{U,h}$ are the amplitude and phase of the upper terminal current, and $I_{D,h}$ and $\varphi_{D,h}$ are the corresponding values for the lower terminal current. Note that (2) has considered harmonic currents, which will flow when supplying nonlinear loads.

A. AC-AC (Common Frequency)

AC-AC conversion can either be at the same or different frequencies. For the former where there is a common dominant harmonic ($h\omega_U = h\omega_D = h\omega$), instantaneous currents flowing through SA1 and SA3 of the nine-switch converter can always be made lower than those of the twelve-switch converter if the following conditions are met.

$$\begin{cases} I_{U,h}^2 + I_{D,h}^2 - 2I_{U,h}I_{D,h}cos(180° - \varphi_h) \le I_{U,h}^2, if\ I_{U,h} \le I_{D,h} \\ I_{U,h}^2 + I_{D,h}^2 - 2I_{U,h}I_{D,h}cos(180° - \varphi_h) \le I_{D,h}^2, if\ I_{D,h} \le I_{U,h} \end{cases}$$

$$\Rightarrow \begin{cases} I_{D,h}/I_{U,h} \le 2cos(180° - \varphi_h), if\ I_{U,h} \le I_{D,h} \\ I_{U,h}/I_{D,h} \le 2cos(180° - \varphi_h), if\ I_{D,h} \le I_{U,h} \end{cases} \tag{3}$$

where $\varphi_h = \varphi_{U,h} - \varphi_{D,h}$ is the phase difference between the two terminal currents. Ideally, $\varphi_h = 180°$, representing the case of one terminal supplying power, while the other absorbs power. Equation (3) then simplifies to $I_{U,h} \le I_{D,h} \le 2I_{U,h}$ or $I_{D,h} \le I_{U,h} \le 2I_{D,h}$. These are conditions that the terminal currents must meet before instantaneous currents through SA1 during T_2 and SA3 during T_1 can be reduced. The switch currents will in fact drop to zero if the system requires $I_{U,h}$ to be equal to $I_{D,h}$ under common frequency mode.

Additionally, it should be mentioned that a current reversal might happen in one of the switches. For example, when $I_{U,h} \le I_{D,h} \le 2I_{U,h}$, $\varphi_h = 180°$, $\varphi_{D,h} = 0°$ and at $t = 0$ s, $i_U + i_D$ through SA3 of the nine-switch converter and i_D through the same notated switch of the twelve-switch converter will both be positive during T_1. Currents therefore flow through the transistors (not anti-parallel diodes) of both converters. On the other hand, $-(i_U + i_D)$ flowing through SA1 of the nine-switch converter will be negative during T_2, while $-i_U$ flowing through the same notated switch of the twelve-switch converter will be positive. Current therefore flows through the diode of the nine-switch converter, while it flows through the transistor of the twelve-switch converter. A switch current reversal has therefore taken place in the nine-switch converter, in addition to its amplitude reduction. Throughout the discussion, it should also be noted that Ref_U and Ref_D have not been considered since they do not influence the cancellation mechanism that happens in the switches. They should however be kept close, where possible, to lengthen T_1 and T_2, during which the cancellation process takes place.

B. DC-DC (Common Frequency)

Logically, dc-dc conversion can be treated as a unique case of ac-ac conversion operating at the common frequency of zero. Reductions of instantaneous currents through SA1 and SA3 of the nine-switch converter are therefore possible when the applied system satisfies (3) with φ_h set to 180°. The latter means i_U and i_D shown in Fig. 2 have different polarities with one terminal supplying power and the other absorbing power. In the ideal case of $i_U = -i_D$, the switch currents through SA1 during T_2 and SA3 during T_1 will be completely cancelled. This is no doubt an advantage gained in addition to saving switches.

C. AC-DC (Different Frequency)

AC-DC conversion is realized by tying the upper terminal of the nine-switch converter to an ac system and its lower terminal to a dc system. Frequencies of the two terminals are therefore different, causing it to be impossible to have switch current reduction at all instants. There can however still be average and squared RMS current reductions, whose reasoning can be explained by considering the example of i_U being in phase with Ref_U and $i_D = I_D > 0$. Following the notations shown in Fig. 2, power is therefore assumed to flow into both

the upper and lower terminals of the nine-switch converter. That causes currents through SA1 during T_2 and SA3 during T_1 to increase when $i_U > 0$, and decrease when $i_U < 0$. The initial impression might hence be a zero increase in switch currents on average, since i_U has equal positive and negative half cycles. This is however only partially true since the "time" factor has not been considered yet.

To explain, it should be mentioned that when $i_U > 0$, Ref_U is also closer to the triangular peak since they are assumed to be in phase. Current through SA3 is therefore increased for a short T_1 interval. On the other hand, when $i_U < 0$, Ref_U is further away from the triangular peak, causing current through SA3 to decrease for a longer T_1 interval. The decrease should ideally cease at zero without allowing the switch current to reverse polarity, which if not prevented, will cause current to increase through the anti-parallel diode of SA3 for the considered example. On average over a fundamental cycle, current through SA3 can thus be reduced so long as amplitudes of the terminal currents are kept nearly the same. The reduction is however not experienced by SA1 during T_2, which is a constant time duration determined by Ref_D.

Other cases like $i_D < 0$, and i_U and Ref_U being out of phase can also be analyzed. The eventual finding is to have both terminals supplying or absorbing powers with nearly the same current amplitude, before an average reduction of switch currents can happen over a fundamental cycle. There must hence be either a source or load attached to the dc-link of the nine-switch converter, as illustrated in Fig. 2. The amount reduced can be determined by performing the following mathematical computations with $\lim T \to 0$ (negative value means reduction).

$$\Delta i_{SA1} = \frac{\omega_U}{2\pi}\{\int[|i_U + i_D| \times T_2/T - |i_U| \times T_2/T]dt\}$$

$$\Delta i_{SA3} = \frac{\omega_U}{2\pi}\{\int[|i_U + i_D| \times T_1/T - |i_D| \times T_1/T]dt\} \quad (4)$$

Substituting expressions from (1) and (2) to (4), and noting that the integration of two signals at different frequencies is zero, then lead to (5).

$$\Delta i_{SA1} = \frac{1}{2}\left(I_D - \frac{2}{\pi}I_{U,1}\right)(1 - M_{oD})$$

$$\Delta i_{SA3} = -\frac{1}{4}I_{U,1}M_U cos\varphi_{U,1} \quad (5)$$

The total average current difference Δi_{SA} between the nine-switch and twelve-switch converters can hence be expressed as (6) after substituting $I_{U,1} \approx I_D$.

$$\Delta i_{SA} = I_D\left(\left(\frac{1}{2} - \frac{1}{\pi}\right) - \left(\frac{1}{2} - \frac{1}{\pi}\right)M_{oD} - \frac{1}{4}M_U cos\varphi_{U,1}\right) \quad (6)$$

The squared RMS switch current differences for the two converters can also be determined by repeating the same mathematical procedure. The derived expressions are listed as follows.

$$\Delta(i_{SA1}^2) = \frac{\omega_U}{2\pi}\{\int[(i_U + i_D)^2 \times T_2/T - i_U^2 \times T_2/T]dt\}$$
$$= \frac{\omega_U}{2\pi}\int\left((I_D^2 + 2i_U I_D) \times T_2/T\right)dt$$
$$= \frac{1}{2}I_D^2(1 - M_{oD})$$

$$\Delta(i_{SA3}^2) = \frac{\omega_U}{2\pi}\{\int[(i_U + i_D)^2 \times T_1/T - i_D^2 \times T_1/T]dt\}$$
$$= \frac{\omega_U}{2\pi}\int(i_U^2 + 2i_U I_D) \times T_1/T\, dt$$
$$= \frac{1}{4}I_{U,1}^2(1 - M_{oU}) - \frac{1}{2}I_D I_{U,1}M_U cos\varphi_{U,1} \quad (7)$$

Substituting $I_{U,1} \approx I_D$ and summing the expressions in (7) then give rise to (8).

$$\Delta(i_{SA}^2) = I_D^2\left(\frac{3}{4} - \frac{1}{2}M_{oD} - \frac{1}{2}M_U cos\varphi_{U,1} - \frac{1}{4}M_{oU}\right) \quad (8)$$

From (6) and (8), the following conditions are necessary in order to gain reductions of switch currents for the nine-switch converter. These are in addition to the requirement of having both terminals supplying or absorbing power.

- The lower Ref_D should be placed closer to the triangular trough in Fig. 4, hence allowing M_{oD} to be larger.
- Depending on the M_U demanded, M_{oU} should be set to the maximum possible of $(1 - M_U/1.15)$.

To illustrate numerically, a simple example assumed has parameters set according to $M_{oD} = 0.6$, $\varphi_{U,1} = 0$, $M_U = 0.8 \times 1.15$ and $M_{oU} = 0.2$. The values computed from (6) and (8) are thus $-0.16I_D$ and $-0.06I_D^2$, respectively, with negative polarity representing reduction. To improve further, the parameters can be redesigned as $M_{oD} = 0.8$, $\varphi_{U,1} = 0$, $M_U = 0.9 \times 1.15$ and $M_{oU} = 0.1$ based on the recommendations derived above. The new values for Δi_{SA} and $\Delta(i_{SA}^2)$ are then $-0.22I_D$ and $-0.19I_D^2$, respectively. On the other hand, if $\varphi_{U,1}$ is improperly set to 180°, values for the two cases will all be positive, representing increases, rather than decreases, of the total switch currents.

D. DC-AC (Different Frequency)

Although dc-ac conversion sounds like a simple swopping of ac-dc conversion, the requirements expected from a nine-switch converter are different. To illustrate, the converter upper terminal is assumed to draw dc power with $i_U = I_U > 0$, while its lower terminal is supplying ac power with i_D phase-shifted from Ref_D by 180°. Currents through SA1 during T_2 and SA3 during T_1 will hence increase when $i_D > 0$, but for a shorter T_2 since Ref_D is now closer to the triangular trough. In contrast, when $i_U < 0$, currents through both switches will decrease, but for a longer T_2 as Ref_D moves away from the triangular trough. Averaging over a fundamental cycle then gives rise to a reduction of total switch current when one terminal supplies, while the other absorbs power. This requirement is clearly different from that demanded by ac-dc conversion.

The amount reduced can be determined by following through the same derivative procedures, but with T_1 fixed and T_2 variable. The expressions obtained are listed as follows, where $I_{D,1} \approx I_U$ has again been substituted to the total average Δi_{SA} and squared RMS $\Delta(i_{SA}^2)$ expressions.

$$\Delta i_{SA1} = \frac{1}{4}I_{D,1}M_D cos\varphi_{D,1}$$

$$\Delta i_{SA3} = \frac{1}{2}\left(I_U - \frac{2}{\pi}I_{D,1}\right)(1 - M_{oU})$$

TABLE II. SUMMARIZED FEATURES AND CRITERIA FOR DIFFERENT NINE-SWITCH SYSTEMS

Types of Energy Conversion	Features / Criteria
Common to All	1. SA2 carries one terminal current during T_1 and another during T_2. No "extra" current is carried.
	Same Terminal Frequencies
AC-AC and DC-DC	1. Currents through SA1 and SA3 will be instantaneously reduced if the applied system satisfies (3). 2. One terminal must supply power, while the other absorbs power. 3. When the terminal currents are 180°-phase-shifted and have the same amplitude, no current flows through SA1 and SA3 during T_1 and T_2.
	Different Terminal Frequencies
AC-AC, AC-DC, DC-AC	1. Currents through SA1 and SA3 cannot be reduced instantaneously.
AC-DC	1. Reduction of average and squared RMS currents can still be achieved according to (6) and (8). 2. Both terminals must supply or absorb power simultaneously, and their current amplitudes should ideally be close. 3. Optimal performance achieved by having a large M_{oD} and $M_{oU} = 1 - M_U/1.15$ for any demanded M_U.
DC-AC	1. Reduction of average and squared RMS currents can still be achieved according to (9) and (10). 2. One terminal must supply power, while the other absorbs power. 3. Optimal performance achieved by having a large M_{oU} and $M_{oD} = 1 - M_D/1.15$ for any demanded M_D.

$$\Delta i_{SA} = I_U\left(\left(\frac{1}{2}-\frac{1}{\pi}\right)-\left(\frac{1}{2}-\frac{1}{\pi}\right)M_{oU}+\frac{1}{4}M_D cos\varphi_{D,1}\right) \quad (9)$$

$$\Delta(i_{SA1}^2) = \frac{1}{4}I_{D,1}^2(1-M_{oD})+\frac{1}{2}I_U I_{D,1}M_D cos\varphi_{D,1}$$

$$\Delta(i_{SA3}^2) = \frac{1}{2}I_U^2(1-M_{oU})$$

$$\Delta(i_{SA}^2) = I_U^2\left(\frac{3}{4}-\frac{1}{2}M_{oU}+\frac{1}{2}M_D cos\varphi_{D,1}-\frac{1}{4}M_{oD}\right) \quad (10)$$

Equations (9) and (10) are no doubt closely similar to those derived earlier for ac-dc conversion. The only differences are a few parameter swopping identified as $I_D \leftrightarrow I_U$, $M_{oD} \leftrightarrow M_{oU}$, $M_D \leftrightarrow M_U$ and $\varphi_{D,1} \leftrightarrow 180° + \varphi_{U,1}$. The last relation spells that $\varphi_{D,1}$ should be 180° rather than zero to arrive at the optimal reduction. This means ac power flowing out, while dc power flowing into the converter. Other current flow combinations can certainly be tried, but the criterion of a terminal supplying and the other receiving power will not change when the nine-switch converter is used for dc-ac conversion.

E. AC-AC (Different Frequency)

AC-AC conversion at different frequencies can be analyzed by assuming one frequency to be prominently lower like for example $\omega_D \ll \omega_U$. In an upper fundamental period $2\pi/\omega_U$, the lower current can hence be approximated as a constant (equivalent to dc). From Section IV(C), reductions of average and squared RMS switch currents will then occur if i_U and Ref_U are in phase, i_D is positive and $I_{U,h} \approx I_{D,h}$. These reductions are however gradually followed by increases in switch currents as i_D becomes negative. The earlier reductions are hence nullified leading to no real advantage for the nine-switch converter when used for ac-ac conversion at different frequencies. The same thought can certainly be tried for the case of $\omega_D \gg \omega_U$. The conclusion drawn will remain unchanged.

F. Summarized Features and Criteria

To comprehend the discussions presented in this section, some important system requirements are summarized in Table II, which must be met before the nine-switch converter can be used efficiently while saving switches. For cases where the requirements are not met, extra switch current burdens shouldered by the nine-switch converter are simply too heavy, hence making the saving in switches meaningless. Application scope of the nine-switch converter is thus limited by its lesser switches, but its performance can still be improved in systems identified sensibly, as proven in this section.

TABLE III. PARAMETERS USED FOR SIMULATION

Parameters	AC-AC	AC-DC
Upper Modulation Ratio M_U	0.85	0.89
Lower Modulation Ratio M_D	0.8	0
Upper Offset M_{oU}	0.1	0.1
Lower Offset M_{oD}	0.15	0.85
Upper Power IN / OUT of System	IN	OUT
Lower Power IN / OUT of System	OUT	OUT
Upper Current i_U	15A	−14.5A
Lower Current i_D	−15A	−15A
DC-Link	Capacitor	DC Source

V. SIMULATION RESULTS

To validate the recommendations suggested in the paper, an example ac-ac nine-switch system operating at a single common frequency was simulated, followed by an ac-dc system operating at different frequencies. Parameters used for the two systems are summarized in Table III with their obtained results organized into four figures. Fig. 5 and Fig. 6 are related to the ac-ac nine-switch system, where the former shows the terminal currents i_U and i_D, and switch currents through SA1, SA2 and SA3. The terminal currents are clearly out of phase, but have the same amplitude. This gives rise to those switch current cancellations detected in Fig. 6 when currents through SA1 during T_2 and SA3 during T_1 are compared with those from the twelve-switch converter shown in the same figure.

The test was then repeated for the ac-dc nine-switch system, whose terminal and switch currents are shown in Fig. 7. Instantaneous currents flowing through the switches are undeniably increased, but over a fundamental period, there are still savings of $\Delta i_{SA} = -0.19I_D$ and $\Delta(i_{SA1}^2) = -0.15I_D^2$ detected. These savings can be explained by referring to Fig. 8, which shows the switch currents of the nine-switch and twelve-switch systems when Ref_U is far away from the triangular peak (see Fig. 4). Time T_1 is therefore comparably longer, during which current through SA3 is also greatly reduced. Its reduction impact is thus greater than the short increase in current experienced by SA3 when Ref_U is closer to the triangular peak in the next half fundamental cycle. Overall current reductions for the nine-switch converter are therefore still possible so long as its applied systems are identified properly based on the recommendations suggested in the paper.

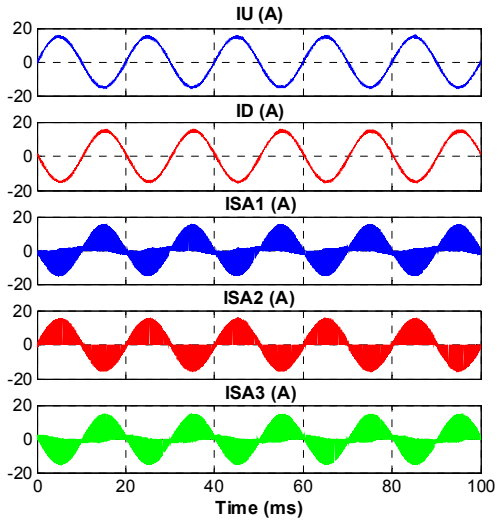

Fig. 5. Terminal and switch currents of ac-ac nine-switch system.

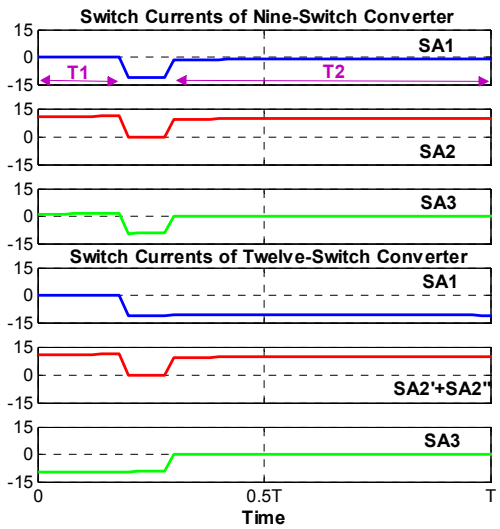

Fig. 6. Switch currents of ac-ac nine-switch and twelve-switch systems in a switching period.

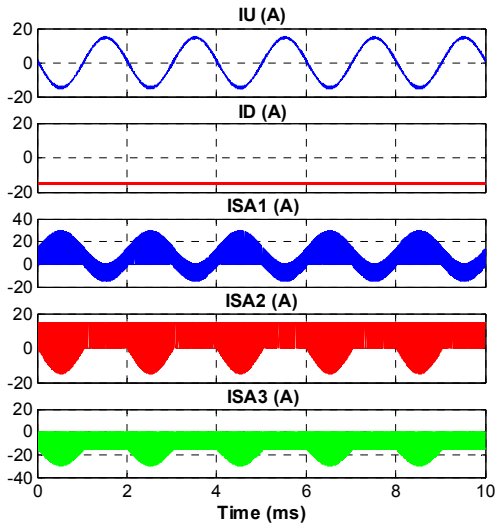

Fig. 7. Terminal and switch currents of ac-dc nine-switch system.

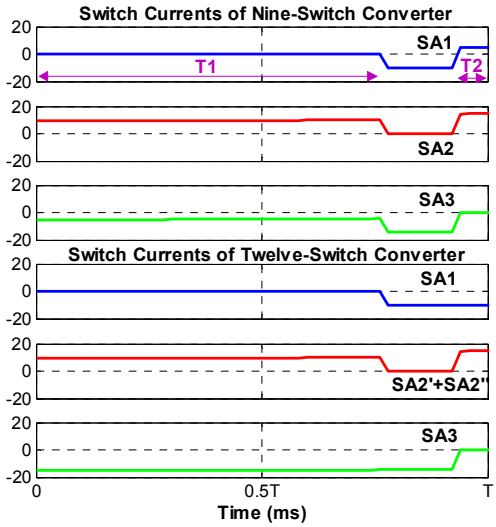

Fig. 8. Switch currents of ac-dc nine-switch and twelve-switch systems in a switching period.

VI. Conclusion

Like all reduced-switch topologies, nine-switch converter has its constraints, and must hence be applied appropriately. To assist in that, switch currents from the converter are evaluated before recommendations are suggested for different ac-ac, ac-dc, dc-ac and dc-dc nine-switch systems. The aim is to keep current stresses low even when using 25% lesser switches.

References

[1] F. Blaabjerg, J. Sander-Larsen, J. K. Pedersen, and H. Kragh, "Reconstruction of output currents and fault detection in a B4-inverter with only one current sensor," in *Proc. IEEE-IAS Ann. Meet.*, 1998, pp, 759-766.

[2] R. Wang, J. Zhao, and Y. Liu, "A comprehensive investigation of four-switch three-phase voltage source inverter based on double fourier integral analysis," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2774-2787, Oct. 2011.

[3] C. B. Jacobina, I. S. de Freitas, C. R. da Silva, M. B. de Rossiter Correa, and E. R. C. da Silva, "Reduced switch-count six-phase ac motor drive systems without input reactor," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 2024-2032, May 2008.

[4] C. B. Jacobina, I. S. de Freitas, and E. R. C. da Silva, "Reduced-switch-count six-leg converters for three-phase-to-three-phase/four-wire applications," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 963-973, Apr. 2007.

[5] T. Kominami and Y. Fujimoto, "Inverter with reduced switching-device count for independent ac motor control," in *Proc. IEEE-IECON'07*, 2007, pp. 1559-1564.

[6] C. Liu, B. Wu, N. R. Zargari, D. Xu, and J. R. Wang, "A novel three-phase three-leg ac/ac converter using nine IGBTs," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1151-1160, May 2009.

[7] C. Liu, B. Wu, N. R. Zargari, and D. Xu, "A novel nine-switch PWM rectifier-inverter topology for three-phase UPS applications," in *Proc. IEEE-EPE'07*, 2007, pp. 1-10.

[8] L. Zhang, P. C. Loh, and F. Gao, "An integrated nine-switch power conditioner for power quality enhancement and voltage sag mitigation," *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1177-1190, Mar. 2012.

[9] P. C. Loh, L. Zhang, and F. Gao, "Compact integrated energy systems for distributed generation," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1492-1502, Apr. 2013.