Simple and Low-Computational Losses Modeling for Efficiency Enhancement of Differential Inverters with High Accuracy at Different Modulation Schemes

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Keywords

«Conduction losses», «Core loss», «DC-AC converter», «Device modelling», «Efficiency», «High frequency power converter», «Modulation scheme», «Power losses», «SEPIC converter»,.

Abstract

The modeling of losses at differential inverters is becoming crucial, especially for enhancing efficiency and reliability of their DC-DC modules. Losses modeling based on sinusoidal duty cycle, at line frequency F_L , without considering differential inverters characteristics and switching frequency (F_s) of their DC-DC modules is not accurate, needs high computational demand, and is not applicable for different PWM modulation schemes. In this paper, a simple and accurate losses modeling for differential inverters is proposed based on two-stage calculation process. In first stage, the losses is calculated based on the switching frequencies for DC-DC modules F_s. Then, in the second stage, the losses is averaged according to operating frequency of differential inverters F_L. The decoupling between both frequencies facilitates the easy insertion of differential inverters characteristics such as static linearization approach and low order even harmonics. Also, it easily obtains the RMS currents in terms of module parameters which reduce the required computational calculations. The proposed modeling is applicable for most modulation schemes such as SVMS, CMS and DMS, thanks to the decoupling property of proposed losses modeling. It is generic for single-phase, three-phase, and multi-phase differential inverters and thoroughly supported efficiency improvement even at modular differential inverters. The flow chart of the presented methodology is explained in detail and effectively applied for many DC-DC modules. For verification, a differential inverter based on SEPIC modules is introduced to validate the accuracy of the proposed losses modeling.

Introduction

Differential inverters have shown noteworthy success in power electronics industry due to their modularity, single-stage and bi-directional power with step-up/down ability [1]. Single/three phase differential inverters utilized boost, buck boost, Cuk, SEPIC or flyback converters have been presented for many applications [2-9]. Moreover, improvements in selective low-order harmonics compensation and accurate mathematical modeling for differential SEPIC inverter have been suggested by authors in many works [10-15]. However, the efficiency of all differential inverters requires supplementary efforts to be higher and has not been thoroughly highlighted in advance. In [16], efficiency is enhanced using soft-switched DC-DC modules by adding LC series resonant circuits at conventional single-phase differential inverters for buck, boost and buck-boost converters. It achieves ZVS operation and validates the differential inverter operation at higher switching frequency with small components. In [9], four-switch SEPIC-based differential inverter with lower components counts is suggested. Advanced Wide-Band-Gap (WBG) devices and advanced transformer cores are proposed to enhance efficiency in [12] and [11], respectively. WBG devices such as Gallium Nitride (GaN) and silicon carbide (Sic), have low on resistances and produces low losses and new cores provide low core losses, eddy losses and hysteresis losses. In addition to continuous modulation scheme (CMS), Discontinuous modulation scheme (DMS) and space vector modulation scheme (SVM) were proposed in [17] and [18], respectively, to enhance the efficiency.

Although, previous works effectively enhanced efficiency of differential inverters using the conventional methods, it did not consider the losses of each component and its effect on the cost and complexity. For example, soft-switching eliminates switching losses but requires additional components, as discussed in [16] which may add cost and complexity. In reality, compromising between soft-switching and hard switching requires accurate modeling of switching losses in order to accurately identify the gained efficiency versus added complexity. Moreover, WBG devises instead of SI devices needs prioritizing between added efficiency and extra cost. These issues requires accurate modeling of current differential inverters and identify the percentage of losses at each part. Then, previous suggested proposals of efficiency enhancement are weighted according to efficiency, cost and complexity.

It's worth noticing that most published work at differential inverters discussed the type of internal DC-DC converters, low-order harmonics and different PWM schemes. It did not effectively fill the gap "losses modeling" because they use general losses equations and obtain inaccurate prediction. In [6], buck-boost differential inverters are compared in terms of losses by calculating RMS currents in the passive elements and switching devices. However, assuming only sinusoidal currents have many limitations. Sinusoidal PWM do not match the real PWM of differential inverters which results from merging the differential inverter characteristics and the utilized DC-DC modules which known as static linearization approach [13]. Also, the losses modeling is limited to continuous modulation scheme (CMS) and did not applicable for DMS and SVMS modulation schemes [17-18].

This paper presents an accurate mathematical losses modeling, which considers PWM scheme, static linearization approach and type of DC-DC converters. This model decouples between the line-frequency and switching-frequency states of differential inverter characteristics, which directly solve the issue of static linearization approach. Also, the proposed decoupling is not only accurately predict real PWM, but it also considers the different PWM schemes because it derives the accurate duty cycle and obtained modulation index. Then, the proposed modeling calculates the power losses directly from the utilized DC-DC converters and their parameters and in turn obtains the average power loss differential inverter over line-frequency range. Doing this facilitates application on other DC-DC converters by repeating only the second stage of losses calculations, which validates a straightforward efficiency-improvement tool by knowing the power loss distribution. Finally, the effectiveness of proposed losses modeling has been investigated, compared and verified by using SEPIC DC-DC converter. The results of three-phase differential inverter has only shown due to page limitations.

Working Principle of Differential Inverters

The concept of differential inverter was firstly appeared in 1999 [7]. A new single-stage single-phase boost inverter was proposed using two bi-directional boost converters. Boost converter modules are connected in parallel at input and differentially connected at the output. Output differential connection decouples the DC component of the output voltage, resulted form unipolar operation of DC-DC converters, and let AC voltage component to appear at the output terminal of differential inverter, as illustrated in Figure 1. This configuration is then applied to many DC-DC converter topologies such as isolated and non-isolated converters and have presented thereafter in many works [2-18].

The PWM of differential boost inverter in [7] and other literature work [2-18], is primarily based on the conventional sinusoidal PWM of voltage source inverter (VSI) to drive the switches of their DC-DC modules [13]. The AC variable duty cycle d_x is generated according to the fundamental frequency $F_L = \frac{1}{T_L}$. Then the switching frequency $F_S = \frac{1}{T_S}$ is being high, compared to fundamental frequency to get small passive elements at promoted DC-DC modules and get compact differential inverter. This is accomplished by comparing saw tooth signal at F_S with d_x at F_L, as shown in Figure 2. The shown PWM is currently known as continuous modulation scheme (CMS). This operation is symmetrical for the rest of the modules at other phases because the only difference is the phase-shift. Therefore, authors in [13], suggested a generalized form of differential inverters that based on replacing the traditional leg of VSI with bi-directional converter, as shown in Figure 3.

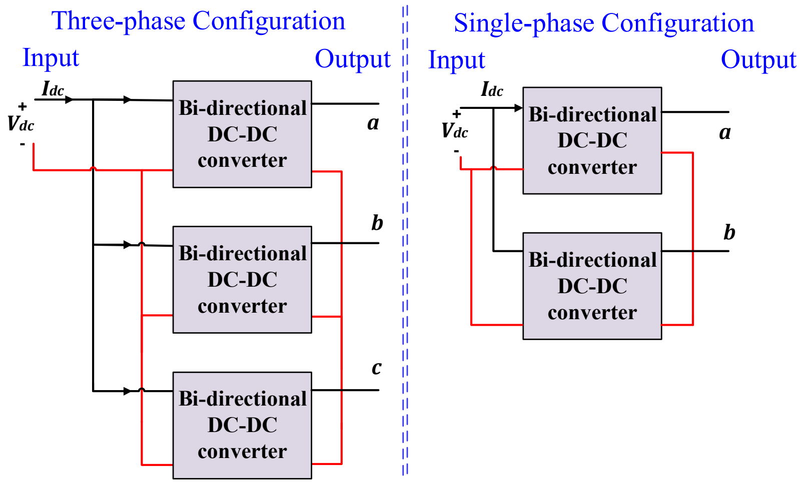

Fig. 1: Three-phase and single-phase differential inverters.

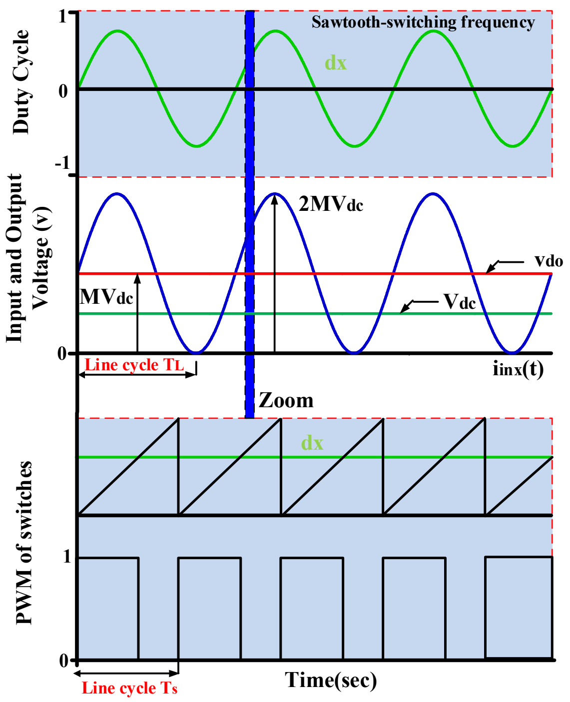

Fig. 2: Sinusoidal PWM of differential inverter that known as CMS.

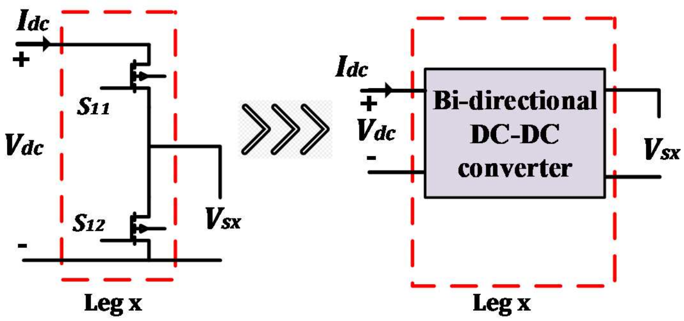

Fig. 3: General configuration of VSI and differential inverters that shows the similarities between them.

Flowchart of Proposed Losses Modeling

The power losses calculation of differential inverter, conducted in [6], is based on the conventional power calculation methods of VSI. Sinusoidal waveform of duty cycle d_x is obtained first by using output voltage of differential inverter (DC and AC component) and input DC voltage and the required voltage gain. Then, the obtained d_x is used with RMS currents of various components of the utilized DC-DC module to calculate average power losses of each component. Although this method considers the characteristics of differential inverter and utilized DC-DC module, it needs high computational burden due to huge math calculation especially using many different integral equations for different waveforms at various components. Also, it have many assumptions that results to considerable mismatch between actual power losses and predictable power losses. Moreover, these calculation should be repeated with different PWM modulation scheme because the obtained power losses calculations is obsessive for CMS. Finally, modeling of power losses at DC-DC modules such as power switches, capacitors and inductors is relatively complicated due to the following deemed differences between differential inverters and VSIs:

- The unipolar operation of DC-DC modules utilized in differential inverters is totally different with VSI legs. Where in VSI, the output voltage on each leg is bipolar.
- The DC component of the output voltage at differential inverter has deemed positive value. However, this value in VSI equal zero.
- The Interact between both frequencies states in differential inverter has different waveform from VSI. Where in VSI, the waveform is generally sinusoidal but in differential inverter it depends on the type of utilized DC-DC module (buck or boost or buck-boost converter)
- The different characteristics between differential inverters and VSIs such as static linearization approach.
- The different PWM schemes such as DMS and SVMS in differential inverters and VSI.

To solve the previous mentioned issues, decoupling between the characteristics of differential inverter and the characteristics of the used DC-DC modules is must. So, in the proposed losses modeling, the power losses calculation has two different stages (Stage-1 & Stage-2). In Stage-1, the utilized DC-DC modules at differential inverter is modeled like conventional DC-DC converters without considering the variable duty cycle d_x. This important notice effectively considers the unipolar operation of conventional DC-DC converters and include the accurate DC component of the output voltage. In Stage-1, the proposed losses modeling for buck converter that presented in [19] is easily used in differential inverters based on buck converter modules. Also, power loss calculation and modeling of other DC-DC converters, such as boost, buck-boost, flyback and SEPIC converters, conducted in [20] is directly used. It is worth noticing that this step (Stage-1) eases power loss calculation by applying direct equations of integrated devices, which were discussed for many DC-DC converters in literature work. Also, the selected DC-DC modules is analyzed for both switching states (on and off) to obtain the connected devices and calculate its power loss based on datasheet parameters and connection intervals.

In Stage-2, the extracted power losses at each interval is averaged on F_L according to the type of PWM scheme and the characteristics of differential inverter. Eq. (1) shows the characteristics of differential inverter at different modulation schemes. Where, h_x is the output voltage component at each module. M_{dc} and M_{ac} are the DC and AC voltage gain of the utilized modules.

$$\left.\begin{array}{l} d_x = \frac{h_x}{1+h_x} = \frac{M_{dc}+M_{ac}sin(\omega t)+M_o}{1+M_{dc}+M_{ac}sin(\omega t)+M_o} \\ d_x \text{ , duty cycle of utilized module at phase } x \\ x = a, b \text{ for single phase} \\ x = a, b, c \text{ for three phase} \end{array}\right\} \quad (1)$$

It's worth emphasizing that both component are equal and depend on the conventional voltage gain of the utilized DC-DC module. M_o is the voltage component that results from different modulation scheme, that given in Eq. 2 for CMS, SVMS and DMS, respectively.

$$
\left.\begin{aligned}
M_o &= 0 \\
M_o &= 0.5\,[\max(m_a + m_b + m_c) + \min(m_a + m_b + m_c)] \\
M_o &= 0.5\min(m_a + m_b + m_c)
\end{aligned}\right\} \quad (2)
$$

Where, m_a, m_b and m_c are the abc component of modulation index at different phases of differential inverter which obtain the static gain signals of the utilized DC-DC modules. Figure 4 illustrates the algorithm of the proposed losses modeling. The link between Stage-1 and Stage-2 is the exact value of duty cycle d_x at each switching interval (T_s), as shown in Figure 4 and Eq. (1). So it's important to define an appropriate time-step T_i for the losses modeling; it is better to use a value small than T_s ten times or more. Increasing the time-step fasten the calculation process but increase the calculation error. On the other hand, decreasing it enhances the accuracy of the model but expands the execution time. Moreover, the actual duty cycle is being higher because the voltage drop in voltage gain (M_{dc} and M_{ac}) which resulted from losses in different components of DC-DC modules. Finally, this process is implemented in Excel sheet and repeated for many variables such as load, as shown in Figure 4.

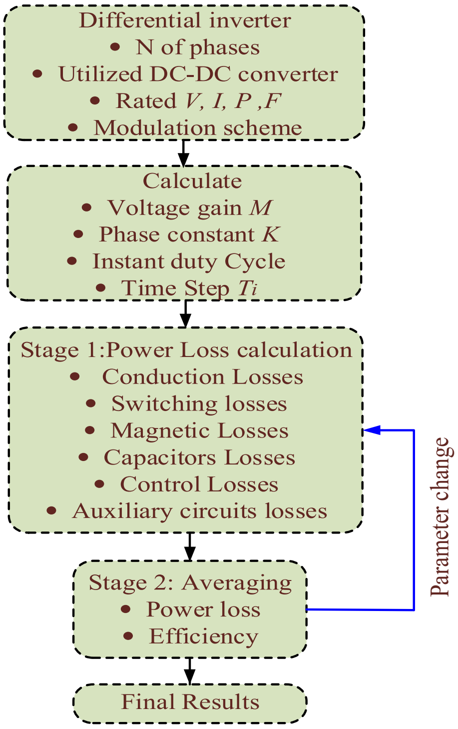

Fig. 4: Flowchart of proposed losses modeling.

Case-Study: Losses Calculation of SEPIC based three-phase Differential Inverter.

A three-phase grid-connected differential inverters based on the three SEPIC modules is presented to validate the proposed losses modeling. The inverter parameters are shown in Table I. The PWM schemes are SVM, CMS and DMS [1]. The gain is $M_{dc} = M_{ac} = 1.5$ and d_x is obtained using Eq. (1). Because $T_s = 20us$, a step time $T_i = 1us$ has chosen in the Excel sheet. The operation modes is then investigated to finalize Stage-1, as illustrated in Figure 5, i.e., for buck-boost SEPIC converter. Doing this at Stage-1, obtains power losses of every component at converters is obtained using traditional equations which used previously at DC-DC converter applications. i.e., the conduction losses of the main switch S_{mx} is obtained from Eq. (3) where, R_{dson} is the on-resistance of the switch, $d_x(t)$ is the duty cycle at this instant. I_D Is the average drain current over one cycle, and, Δi_D is the ripple component of switch current. Also, the switching losses are obtained based on Eq. (4). t_{rise},t_{fall} and C_{oss}, are the rise time, fall time and drain source capacitance, respectively.

$$P_{cond}(t) = R_{dson}d_x(t)[I_D{}^2 + \frac{\Delta i_D{}^2}{12}] \quad (3)$$

Table I: System parameters of studied differential inverters

Parameter	Rated power	Input DC voltage	Grid voltage	Line Frequency
	P	V_{dc}	V_{LL}	F_L
Value	$0.2 - 1.6kW$	$100, 120\ V$	$200\ V$	$60Hz$
Parameter	Converter Inductor	Output Capacitor	Grid inductance,	Switching Frequency
	L_x	C_{ox}	L_{gx}	F_s
Value	$200\mu H$	$14\mu F$	$4mH$	$50\ kHz$

$$\left.\begin{aligned} P_{sw}(t) &= P_{swon} + P_{swof} + P_{coss} \\ P_{swon}(t) &= \frac{1}{6}t_{rise}F_{sw}V_{ds}\left[I_D - \frac{\Delta i_D}{2}\right] \\ P_{swof}(t) &= \frac{1}{6}t_{fall}F_{sw}V_{ds}\left[I_D + \frac{\Delta i_D}{2}\right] \\ P_{coss}(t) &= 0.5\ C_{oss}V_{ds}{}^2 \end{aligned}\right\} \quad (4)$$

Eq. (5) are for body diode losses of S_{mx}. In both, I_F is average forward current over T_s,V_F is the forward voltage, Δi_F is the ripple component, t_{dead} is the dead time between main and synchronous switch, and Q_{rr} is the reverse recovery charge. Losses of other components is covered in [19]. Finally, Stage-2 of proposed modeling averages losses according the different modulation schemes.

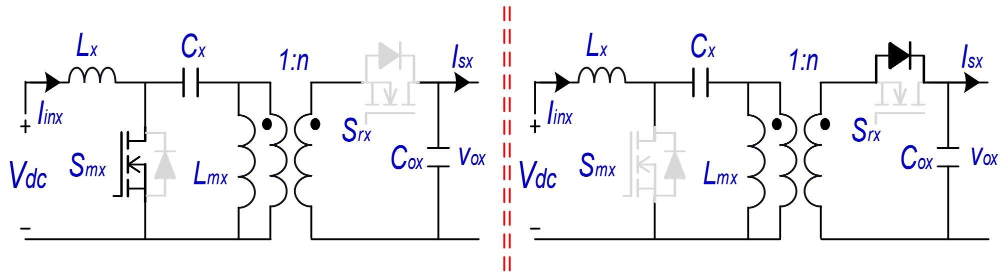

Fig. 5: Switching states of the SEPIC buck-boost converter at differential inverter.

$$\left.\begin{aligned} P_{cond}(t) &= d_x(t)I_FV_F \\ P_{sw}(t) &= P_{swon} + P_{swof} + P_{Qrr} \\ P_{swon}(t) &= t_{dead}F_{sw}V_F\left[I_F - \frac{\Delta i_F}{2}\right] \\ P_{swof}(t) &= t_{dead}F_{sw}V_F\left[I_F + \frac{\Delta i_F}{2}\right] \\ P_{coss}(t) &= 0.5\ V_{ds}F_{sw}Q_{rr} \end{aligned}\right\} \quad (5)$$

Results and Discussion

The results of SEPIC based differential inverter is shown here. Figure 6 shows the waveforms of inverter at different modulation schemes. It's worth noticing that d_x waveforms is different and then losses will be different. Therefore, using proposed modeling calculates power losses at Stage-1 for full period then averages the losses based on the type of modulation scheme is easy and direct solution. Figure 7 shows the efficiency of the differential inverter using the proposed losses modeling, simulations and experiments. It’s worth noticing that the difference between theoretical, simulated and experimentally measured efficiency is small due to the accuracy of proposed model. Although the error between calculated efficiency between proposed model and experiments results from the unknown parasitic of the circuits and external wires, the proposed model is accurate because it gives the same performance with experimental measured efficiency.

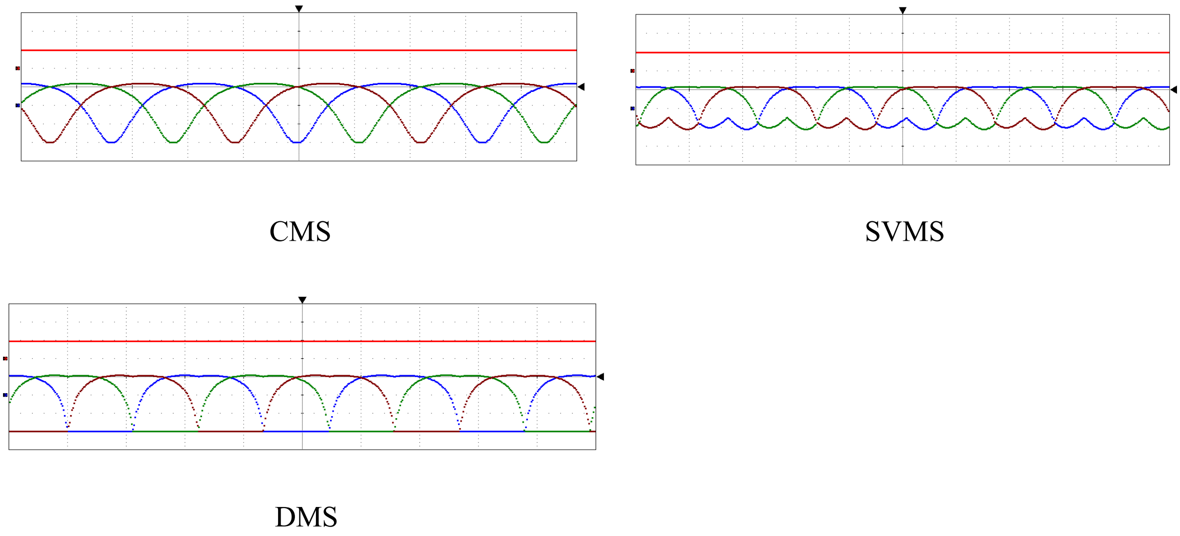

Fig. 6: Waveforms of DC voltage gain $M_{dc}$and variable duty cycle d_x ($d_a, d_b$and d_c) of SEPIC based differential inverter, respectively.

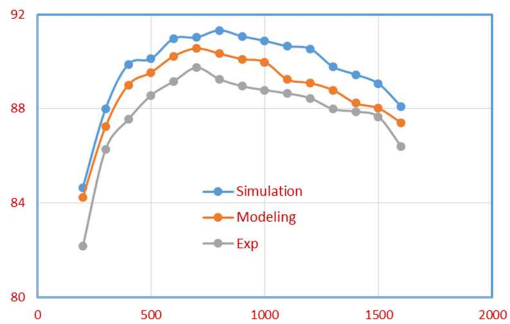

Fig. 7: Efficiency comparison at CMS modulation.

Figure 8 shows the simulation results for CMS, SVMS and DMS using proposed losses modeling. It’s worth noticing that the DMS modulation gives the best efficiency which exactly matched with results at [17]. The loss-division is also investigated using proposed modeling for the utilized components, as shown in Figure 9-11, at different input voltage levels and different power rating at CMS modulation. It includes modeling of switches such as MOSFET devices, magnetics such as input inductor and HFT, and passive elements such as capacitors, extra. At CMS, The dominant power losses for $V_{dc} = 100V$ are associated with HFT with 29.19%. Then the power losses of input inductor and switches are 27.9% and 26.95%, respectively. It is worth mentioning that the power losses of main switches (17.05%) are larger than those of synchronous switch (9.9%) due to its real PWM waveform of differential inverter. For higher input DC voltage, the power loss of HFT increased to 29.9% at $V_{dc} = 120V$, respectively. The same finding is for inductor, 30.24%. However, the power losses of switches are reduced to 25.54% and 24.83%. This finding is important to express the effect of input DC voltage on overall efficiency. Figure 10 and 11 present the power losses division at different power ratings, $P_o = 0.8kW$ and $P_o = 0.4kW$, respectively. These findings are significant at the differential inverter because the proposed modeling predicts the sources of power loss at many operating conditions accurately.

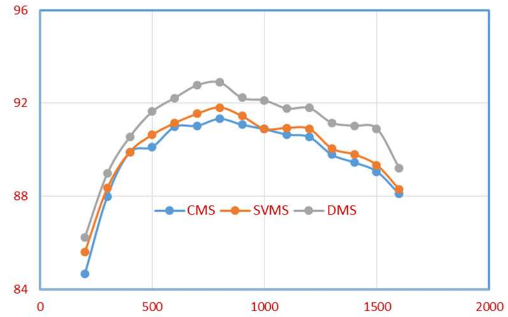

Fig. 8: Efficiency comparison at CMS, SVMS and DMS using proposed modeling.

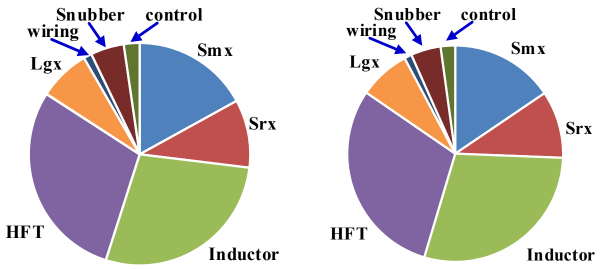

Fig. 9: Loss-distribution at $V_{dc} = 100, 120$ V and $P_o = 16kW$

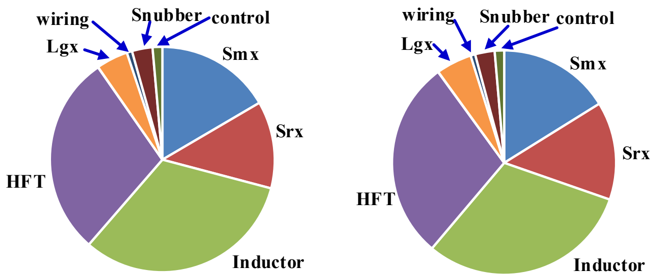

Fig. 10: Loss-distribution at $V_{dc} = 100, 120$ V and $P_o = 0.8kW$

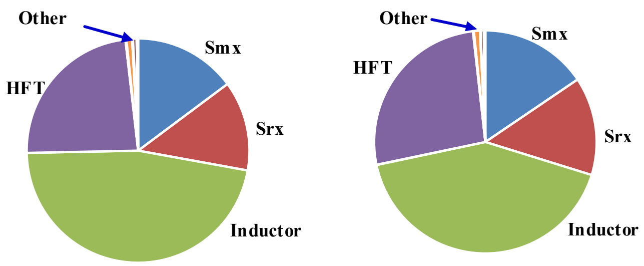

Fig. 11: Loss distribution at $V_{dc} = 100, 120$ V and $P_o = 0.4kW$.

Conclusion

An accurate losses modeling for differential inverters is presented. It's based on decoupling between differential inverter switching states at line-frequency and switching-frequency. It eases the power loss calculation, which does not exist in traditional losses models. The added features are the direct calculations that can be developed quickly, even at different phases and different DC-DC modules for differential inverter topologies. It obtains the current equations through components in terms of module parameters. The proposed model can be applied for single-phase, three-phase, and multi-phase differential inverters because it depends on its integrated DC-DC modules. A case-study using three-phase SEPIC differential inverter is introduced to validate the proposed model's accuracy. Finally, the presented methodology's flow chart is generalized and applied to other DC-DC converters to facilitate the power losses calculation.

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