Modulation Selection Procedure Applied to a High-Power Adjustable High-Speed Drive

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Abstract

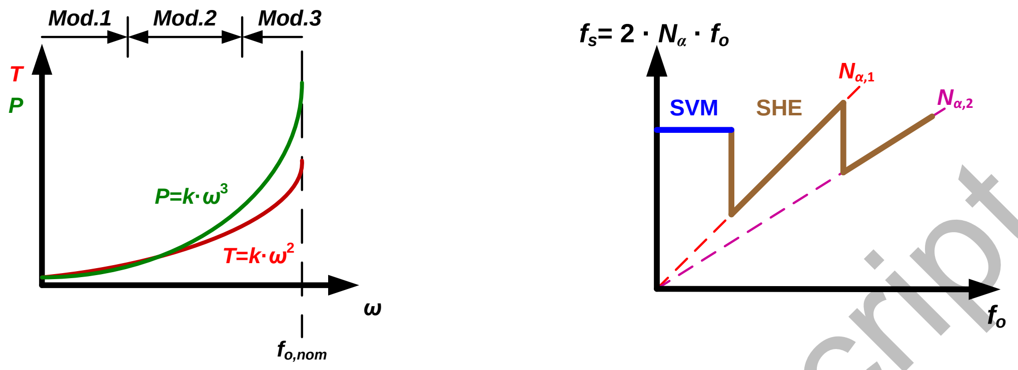
This paper proposes a systematic procedure to evaluate, compare and select different modulation techniques for a medium voltage variable speed drive. Several indicators are proposed to be analyzed, mainly based on thermal analysis, voltage limitations, dc bus evaluation and load current quality. The suggested procedure is evaluated on a simulation based analysis in a 6.6 kV adjustable speed drive system with a 5-level H-bridge neutral point clamped (HNPC) inverter topology and diode front end (DFE) as rectifier. The use of selective harmonic elimination (SHE) with different number of angles and space vector modulation (SVM) is assessed depending on the load demands (output frequency, modulation index, etc.).

Introduction

As power electronics have evolved into a mature technology [1], adjustable speed drives have increased their penetration levels into industry applications [2]. Moreover, the power demanded by the applications is also increasing. In some of these cases, high output speeds are required by the load. When this happens, high output adjustable speed drives are used, which allow to eliminate the possible use of mechanical gearboxes that decrease the system efficiency and reliability [3].

Nowadays, a wide range of solutions in terms of machine topologies, converter topologies, control and modulation techniques can be found in the scientific specialized literature or among manufacturers, in order to fulfill all the applications' requirements [4]. Furthermore, in the case of adjustable high-speed drive systems, a proper trade-off among machine, converter topology, modulation strategy and control needs to be performed [3]. This paper is focused on the proper modulation strategy selection, for a high-speed adjustable speed drive modulation techniques (with an operation range from 0 Hz to 250 Hz applied to a quadratic torque load (such as pumps, fans or compressors [5], Fig. 1a) and using a 5-level H-bridge neutral point clamped (5L HNPC) converter [3], [6].

Regarding the modulation technique selection, the most common methods are space vector modulation (SVM [7]) and selective harmonic elimination (SHE [8]) for high power drives. Pulse width modulation (PWM) is considered as a particular case of SVM [9] in the results. Furthermore, regarding the SHE methods, the number and range of harmonics that could be eliminated can change [10], [11], which modifies completely the behavior and performance of the modulation implying the necessity to carefully select the SHE pattern. Additionally, among all the alternatives in high-power and high-speed applications, the modulation pattern usually changes as the output frequency evolves depending on the operation point, since for instance, power losses might limit the converter operation, or voltage quality might turn out not to be acceptable (Fig. 1b). As an example, in railway applications, SVM alternatives are used at lower output frequencies; afterwards, SHE methods are applied at higher frequencies; and then finally, with square wave or full wave at the highest frequencies, when power losses become critical [10]. Therefore, selecting a proper modulation technique at the different operating ranges of the drive leads to better semiconductor optimization, and also higher converter available output power [11] with better performance.



a) b)

Fig. 1. Modulation evolution example with the load. a) Modulation change regions. b) Switching frequency and output frequency relationship.

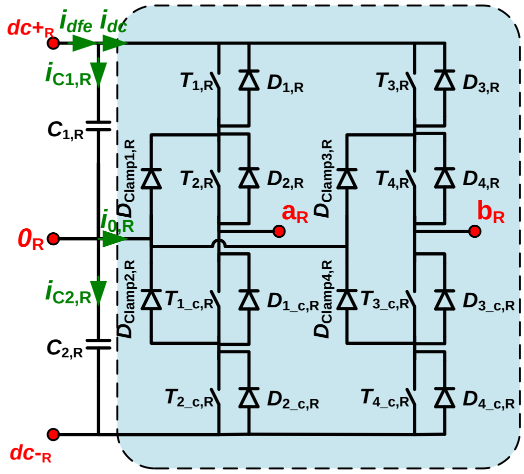
Concerning high-power applications, on the one hand, SHE is the predominant modulation technique since acceptable output waveform quality is achieved with a low number of commutations [12], [13] without further degradation of the control performance. However, the use of SHE solutions demands a considerable off-line effort to calculate the required angle sets, which depending on the number of levels of the converter, considerably increases the complexity for converging solutions [14]. Additionally, not increasing the number of commutations and performing an efficient neutral point control algorithm can become a problematic task. On the other hand, using PWM-SVM alternatives decreases the complexity brought by the angles' calculation of the SHE at the design stage, but needs a higher switching frequency to output frequency ratio at normal operation in order to synthesize the desired voltage with reasonably good harmonic distortion; hence, the number of commutations increases compared with SHE techniques. However, in certain applications, SVM can be pointed out as a competitive solution.

Moreover, from the control performance point of view, it is found that the drive can work with the proposed modulation strategies, changing on-line from one pattern to another at defined frequencies during normal operation, keeping the same control philosophy and without any degradation in the system performance [10].

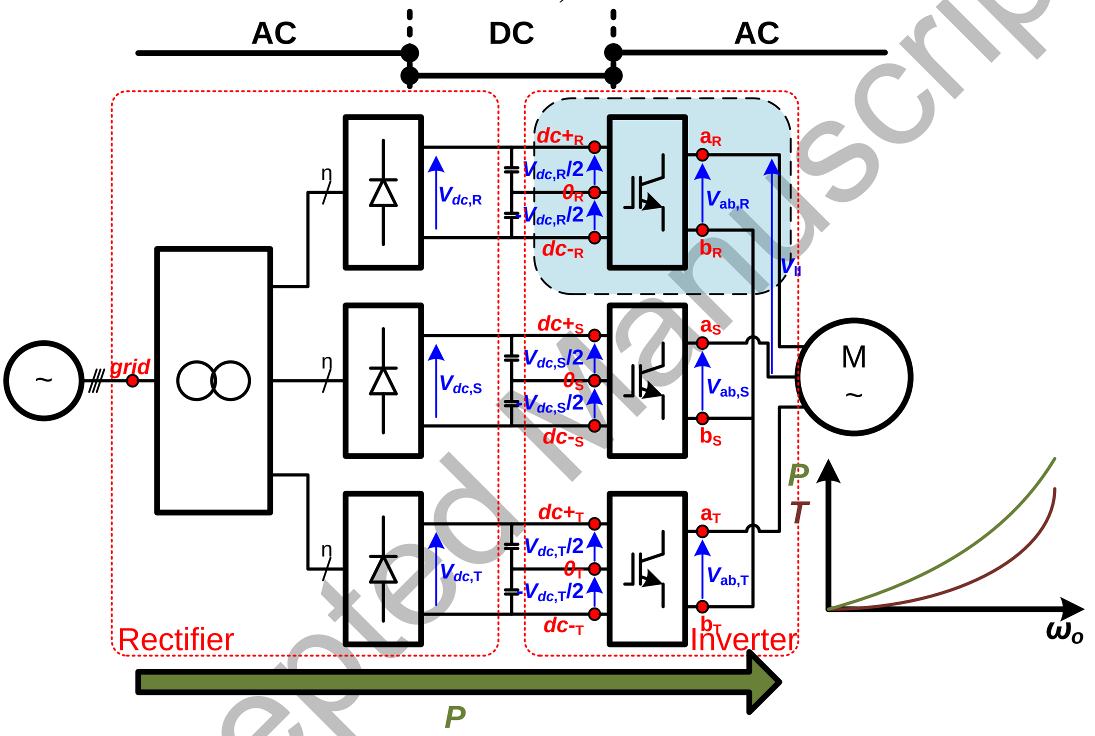
Consequently, the main goal of this paper consists of presenting a simulation based analysis procedure, capable of preliminarily selecting the most proper modulation technique for each output frequency range of an adjustable speed drive. This procedure is applied into a specific scenario and the obtained results are served throughout the paper.

Comparison Scenario

The procedure is applied to a high-power and high-speed drive with a quadratic torque vs. speed evolution [5] (see Fig. 2a). The converter supplies a 6.6 kV-6 MW high speed induction machine which requires a fundamental frequency voltage waveform that can vary from 0 Hz to 250 Hz.



a)



b)

Fig. 2. Analyzed converter configuration scheme. a) One phase inverter system; 5L HNPC inverter branch. b) Whole three phase structure.

The inverter topology is selected to be the 5L HNPC (see Fig. 2) [3] based on the association of three single phase H-bridge converters. Each H-bridge is formed by two 3L NPC [15] legs with IGBTs used as controlled switches. One of the outputs of each H-bridge is connected together in star connection, connecting the other output of each phase to the load. Regarding the rectifier topology, a DFE configuration is selected. The DFE topology (6 pulses, 12 pulses, 24 pulses, etc.) [16] does not have a relevant influence on the evaluated indicators for the inverter choice, therefore the DFE configuration is not considered. Nevertheless, the use of a transformer is compulsory in order to achieve three isolated dc sources to feed the dc bus of each 5L H-bridge.

Consequently, Table I summarizes the selected motor and power converter characteristics, calculated from [17] to achieve an output voltage of 6.6 kV and a power of 6 MW.

Table I. Selected induction motor/converter parameters [17].

POWER	6 MW	**TORQUE**	3819.7 NM
VOLTAGE	6.6 KV	**CURRENT**	606.47 A
POWER FACTOR	0.8654	**STATOR FREQUENCY**	250 HZ
PAIRS OF POLES	1	**STATOR RESISTANCE**	0.0403 Ω
STATOR LEAKAGE INDUCTANCE	0.60968 MH	**ROTOR RESISTANCE**	0.0468 Ω
ROTOR LEAKAGE INDUCTANCE	0.81059 MH	**MAGNETIZING INDUCTANCE**	0.0188 H
DC BUS TOTAL CAPACITY	4 MF	**DC BUS VOLTAGE**	5600 V
SVM SWITCHING FREQUENCY	1 KHZ	**SWITCHES RATED VOLTAGE**	4.5 KV

Evaluated Modulation Techniques

The high-speed and high frequency range of the considered application leads to the consideration of space vector modulation (SVM [18], where the injection of the third harmonic is assumed) and selective harmonic elimination (SHE, [13]) techniques. Moreover, among the SHE techniques, a different number of angles (N_α) solutions per H-bridge are proposed: six (SHE6) and two (SHE2) calculated angles per 90º of fundamental waveform. All the modulation methods do have their own dc bus neutral point voltage balancing algorithm implemented.

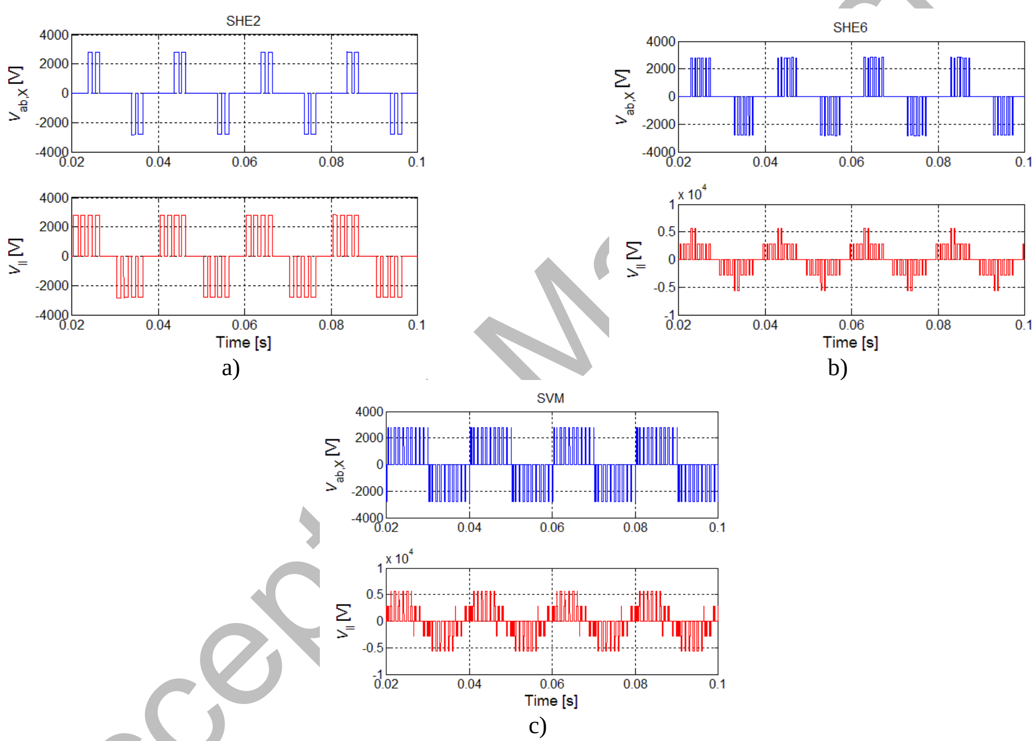


Fig. 3. Analyzed modulation techniques examples with output frequency of 50 Hz (H-bridge output voltage, blue; output line-to-line voltage, red). a) SHE with two calculated angles. b) SHE with six calculated angles. c) SVM with the injection of the third harmonic.

Furthermore, it needs to be remarked that the modulation index is established to go from 0 to 1, where 1 corresponds to the output voltage value achieved by square wave utilization, which means one commutation in the whole H-bridge per 90º of the fundamental period:

$$m_a = \frac{\pi}{4} \cdot \frac{\sqrt{2} \cdot V_{X,ab}}{V_{dc}} \quad (1)$$

In order to perform dc bus neutral point control, each modulation alternative follows different strategies.

- Regarding the SVM alternative, for each modulation period (thus, switching frequency dependent), the most suitable redundant vectors are selected in order to correct the neutral point in the desired direction.

- On the contrary, SHE methods make a prediction of the neutral point for the next 90º of the fundamental period and select the most suitable redundant vectors sequence based on [19]. In order to avoid possible prediction and measuring uncertainties, a hysteresis method is used to define the correcting trend of the neutral point voltage.

Proposed Comparison Procedure

Fig. 4 shows the procedure proposed to evaluate, compare and select the modulation techniques in relation to the converter output frequency. As it can be observed, five main procedure inputs are required: load characteristics, semiconductor and heatsink definition, converter topology and modulation specifications. These proposed characteristics are mainly focused on the converter variables and parameters comparison and evaluation. Accordingly an evaluation like this could be executed concentrating on the effects of the modulation in the machine behavior (for instance, switching frequency may have influence on iron losses, vibration, etc.).

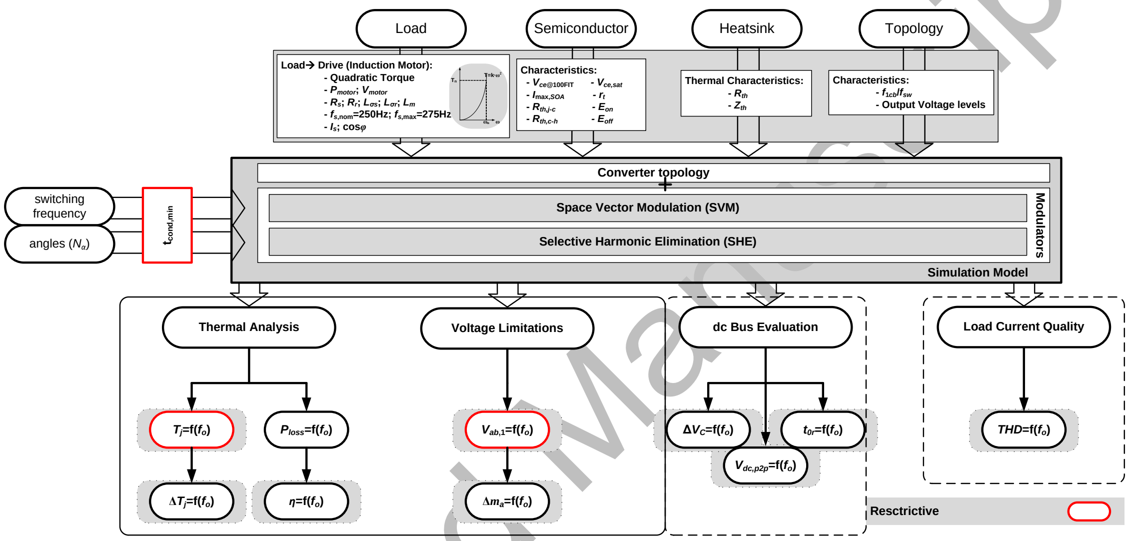


Fig. 4. Proposed data generation diagram for the modulation techniques comparison procedure.

The procedure consists of the comparison of four main variables' evolution, obtained by extrapolated data from simulation results [11]: thermal behavior, voltage limitation, dc bus evaluation and load current quality. Accordingly, from each of them, different indicators are calculated, which allows the designer to select the most suitable modulation technique for each output frequency according to defined criteria (potentially specific for each designer). Furthermore, some of the indicators (marked in red in Fig. 4) can contribute to discard some modulation techniques for some specific operating points.

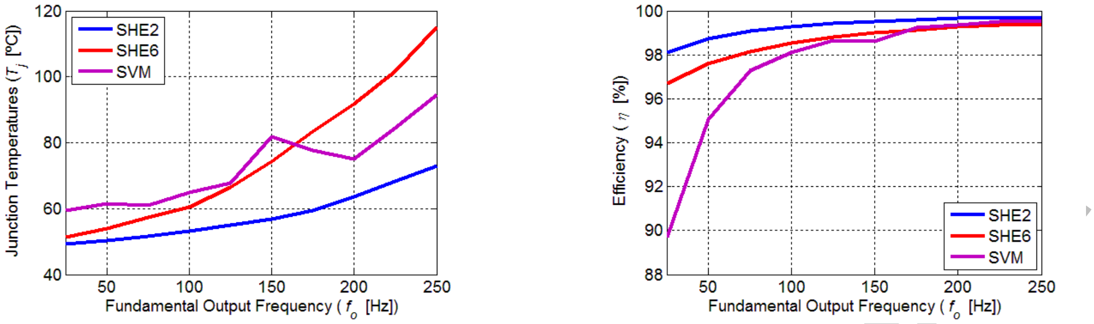
In the following sub-sections, the indicators' explanation is further developed. In addition, achieved results applied to the 5L HNPC converter topology (see previous sections) are presented, in order to give an idea of the application of the procedure potential.

Thermal Analysis

One of the main aspects to be studied is the thermal behavior of different modulations techniques applied to the analyzed converter topology. Therefore, in order to provide insight of the behavior of the modulation alternatives, the below-mentioned indicators are proposed. Within the thermal analysis, two main parameters are proposed to be analyzed (by means of a power losses estimator [20]).

- The first one (Fig. 5a) corresponds to the most critical semiconductor's junction temperature limitation. If the most critical semiconductor is identified, the whole converter operation restrictions can be limited. Therefore, if a maximum critical junction temperature is exceeded, the modulation technique utilization needs to be dismissed. This parameter does also reveal the temperature margin of the most critical semiconductor of the converter, which can be understood as the stress the most critical semiconductor has; thus, giving an indication of the converter lifetime.

- Finally, if converter semiconductors' power losses are estimated, the converter silicon efficiency ratio can be examined (Fig. 5b). Therefore, the highest value of this indicator, the better. Hence, this calculation is interesting to be taken into account for the final modulation techniques selection.



a) b)

Fig. 5. Thermal evaluation. a) Semiconductors' maximum junction temperature. b) Converter efficiency.

Therefore, analyzing the obtained results, if a maximum acceptable junction temperature of 110ºC is defined, SHE6 exceeds the junction temperature limitation with high output frequencies. Therefore, the use of SHE6 for high output frequencies is discarded due to thermal constraints. SHE results can be explained due to the switching frequency and output frequency constant relationship for both modulations, which makes the number of commutations increase if output frequency augments. The SVM results do mostly correspond to the output current increase as the output frequency grows.

Closely related to this specifications, SHE2 always offers the biggest junction thermal margin. As the output frequency increases, where the thermal constraint is supposed to be more important, SVM offers better junction temperature margin than SHE6. Added to this, SHE2 serves the best silicon efficiency ratio, thanks to a smaller number of commutations. Afterwards, SHE6 offers a better ratio value than SVM, until the resultant switching frequency of the SHE6 (which evolves with the output frequency) becomes bigger than the switching frequency employed by SVM, around 175 Hz (see Fig. 1b).

Voltage Limitations

Apart from the thermal evaluation, appearing possible voltage limitations can be identified as a meaningful characteristic of the modulation methods. Fig. 6 shows the voltage synthesizing limitations of each modulation technique. Each modulation strategy is able to create different modulation index maximum values (thus, fundamental harmonic maximums) depending on the commutation constraints of each method (dc bus voltage, minimum conduction times, etc.). Therefore, the margin from the required modulation index to the practically attainable maximum modulation index is different for each modulation method. This margin is interesting at high modulation indices, where a modulation index gap needs to be saved for control purposes.

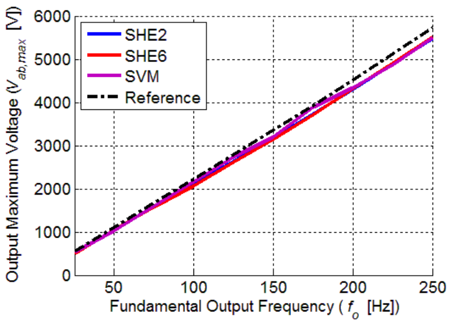


Fig. 6. Output maximum H-bridge voltage limitations evaluation.

Table II. Modulation technique limits.

	$m_{a,max}$
SHE2	0.995
SHE6	0.935
SVM	0.905

In the treated case, the three analyzed modulation techniques are able to offer the voltage values asked by the load in the whole application range, V_{ll}=6.6 kV (see Table II, where maximum modulation indices are served). However, it needs to be remarked that although all of them are capable of reaching the required modulation index, SVM makes use of the third harmonic injection in order to accomplish the maximum modulation index demanded by the load. Hence, analyzing Fig. 6 and Table II, SHE2 become the best alternative in terms of available extra modulation index gap to be used for control purposes, followed by SHE6 and SVM.

DC Bus Evaluation

The effect on the dc bus voltage caused by each modulation technique (ripple voltage related to the use of the DFE and H-bridge configuration) and the corresponding neutral point control algorithm is another appreciable characteristic to be evaluated and compared. Accordingly, the following indicators are proposed:

- The instantaneous dc bus capacitors voltage difference (ΔV_C, Fig. 7a), which is an important parameter to be considered in order to evaluate the dc bus neutral point balancing performance of different modulation alternatives.
- The total dc bus voltage ripple ($V_{dc,p2p}$), which defines the maximum steady-state operating dc voltage to be handled by the semiconductors of the converter, Fig. 7b. In this case the low frequency voltage oscillation at two times the output frequency due to the considered converter topology is dominant (single phase H-bridge configuration) compared to the impact of the applied modulation strategy (voltage ripple at the switching frequency).
- The neutral point balancing response time (t_{0r}, Fig. 7c), which is used as an indicator of the maximum unbalance that the dc bus voltages must withstand transiently. This response time is obtained from the neutral point balancing transient response provided by different modulation strategies when a dc bus capacitor's voltage unbalance step (10% of the capacitor nominal voltage value) is applied.

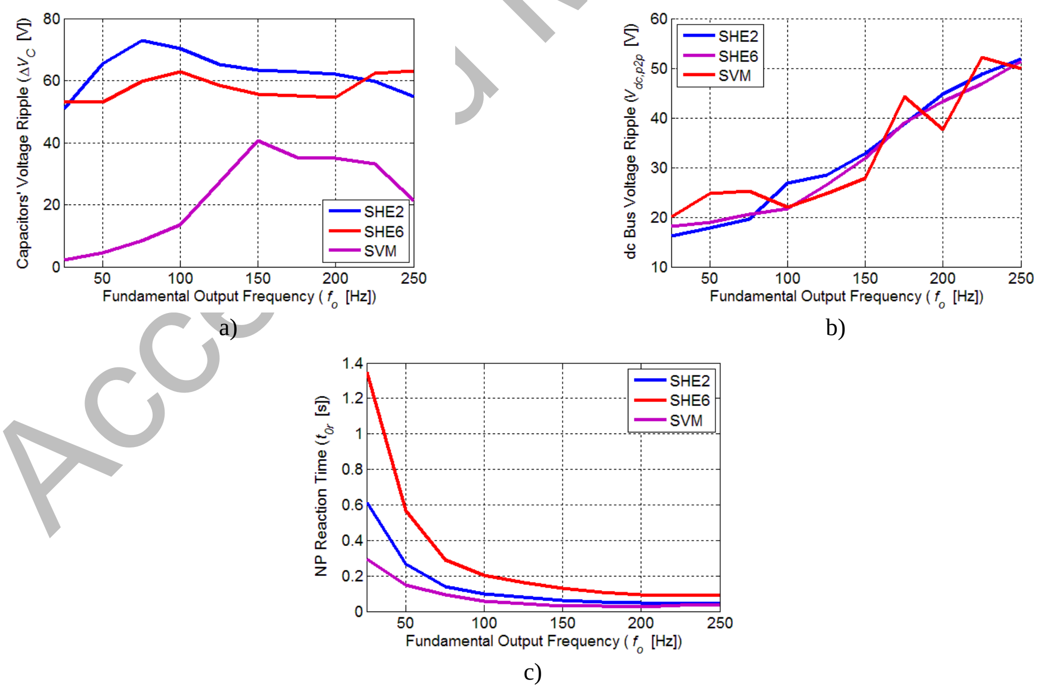


Fig. 7. DC bus evaluation. a) Capacitors' voltage difference, due to modulation effects. b) DC bus voltage ripple. c) Neutral point balancing response time.

Regarding the dc bus evaluation indicators, SVM presents the best performance. Regarding the instantaneous dc bus capacitors' voltage difference (ΔV_C), the SVM modulation provides lower values than the SHE modulations with a maximum at around f_o=150 Hz. Additionally, both SHE techniques share an almost constant ΔV_C in the whole output frequency range due to fixed hysteresis level used in the neutral point balancing strategy [19]. From the total dc bus voltage ripple point of view, the same behavior for all evaluated modulations is observed due mainly to the low frequency dc bus oscillation at two times the output frequency, proportional to the active power demanded by the load when using a H-bridge [21].

Finally, the neutral point balancing response time reflects that SHE6 offers the worst reaction time results, while SVM provides the best performance. This behavior can be explained due to SVM the fact that the SVM tries to correct the capacitors' voltage unbalance every switching period, while SHE techniques need at least a quarter of the output period to start correcting the neutral point unbalance [19]. Obviously, at higher output frequencies, the response time for the evaluated modulation strategies get closer as the SVM switching period becomes closer to a quarter of the output period.

Load Current Quality

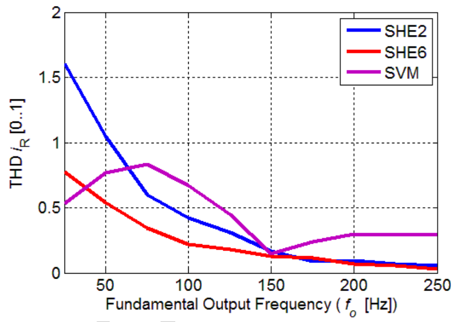
The load current quality can really be presented as an important parameter to be considered in order to know the suitability of a modulation technique since it can have an important impact over the semiconductors and motor working conditions (maximum current to be switched, current harmonics generating copper and iron losses on the motor, torque ripple, etc.). In order to compare the quality of the current for each modulation, the motor phase current THD [11] (Fig. 8a) is analyzed,

$$\mathrm{THD}i\,[\%] = \frac{\sqrt{\sum_{h=2}^{\infty} (I_h)^2}}{I_1} \cdot 100 \cdot \qquad (2)$$

Furthermore, it needs to be pointed out that current THD can be defined as an image of the line-to-line voltage weighted total harmonic distortion (WTHD) value,

$$\mathrm{WTHD}v\,[\%] = \frac{\sqrt{\sum_{h=2}^{\infty} \left(\frac{V_h}{h}\right)^2}}{V_1} \cdot 100 \,, \qquad (3)$$

as it is demonstrated in Fig. 8b.



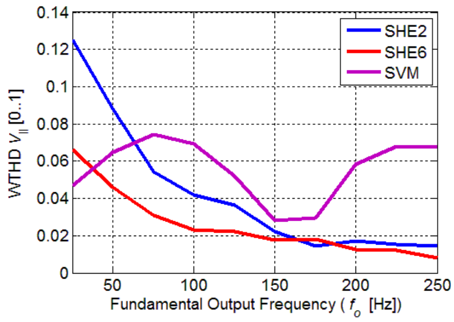


Fig. 8. Load current/voltage quality. a) Output current THD. b) Line to line voltage WTHD.

The obtained results show, in this case, that the SVM can be highlighted as the best alternative at low frequencies, while SHE6 appears as the best modulation technique for a middle output frequency range. Finally, for higher output frequencies both SHE alternatives turn out to be competitive. From the current THD point of view, the SHE6 modulation strategy provides better performance that the SVM modulation from a relatively low output frequency (f_o≈35 Hz).

Comparative Study

After evaluating the four defined variables for the considered modulation technique, the proposed procedure concludes by performing a final comparison. This comparison is performed by weighting the different evaluated indicators according to the designer criteria which are usually very dependent on the application requirements. The aim is to identify the best suited modulation strategy according to the defined criteria on a certain output frequency range, Fig. 9 (prioritizing of the current quality in this case). Note that the operation points restricted for each modulation technique due to the thermal constraints, the voltage synthesizing restrictions, etc., must be taken into consideration so as to know if the modulation technique can be applied on the expected output frequency range. For instance, in the system analyzed on this paper (Table I), the use of SHE6 is restricted for output frequencies higher than 200 Hz due to thermal limits.

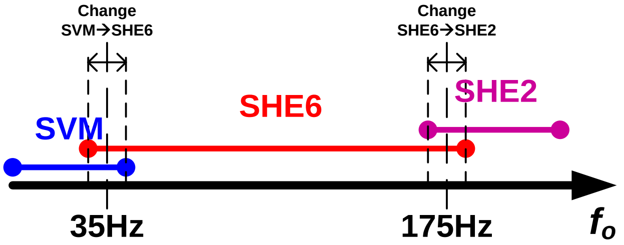


Fig. 9. Modulation techniques' evolution with the output frequency.

As final result of the applied modulation selection procedure for the example considered in this paper, first the SVM technique is selected up to an output frequency around 35 Hz; SVM is normally applied at low frequencies and specially around zero speed to guarantee the right behavior of the motor control systems. Afterwards, SHE6 is recommended to be selected. Actually, although SVM can be thought to have better output current spectrum than SHE6, this last one offers a better quality after this selected output frequency borderline. Furthermore, this selection is reinforced by the fact that the SHE methods provide better efficiency at low output frequency values. Finally, SHE2 is selected as the preferred modulation technique above 175 Hz. Above this frequency, because both SHE techniques offer almost the same current qualities, efficiency becomes the driving indicator for the selection of SHE2, even before the SHE6 modulation is restricted due to thermal constraints.

As mentioned, the relevance of each evaluated parameter needs to be defined depending on the application characteristics. Therefore, if any of the inputs of the procedure (Fig. 4) is changed, the weights given to each studied characteristic can be drastically altered.

Conclusions

In this paper a procedure to evaluate, compare and select the most suitable modulation technique to be applied into the output frequency operation range of an adjustable speed drive is presented. The application of this procedure is illustrated for a high-power, medium-voltage, high-speed drive system supplying a quadratic torque load where the considered inverter topology is the 5L HNPC.

The results demonstrate clearly how the performance of the drive system can be optimized according to certain design criteria by simply modifying the output frequency range where the different considered modulation techniques are applied. In the considered example, SVM is stated as the most convenient modulation technique for the lowest output frequency range due to its lower current harmonics content; while the SHE alternatives stand out as more appropriate as the output frequency increases due to the higher output voltage synthesizing capacity and lower semiconductor power losses.

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