Series Hybrid Powertrain Based on the Dual Two-Level Inverter

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Abstract— **A multilevel converter in the 'dual two level' configuration is proposed as the core of a hybrid series powertrain. The generation system of the powertrain is constituted by an internal combustion engine (ICE) connected to a three-phase permanent magnet synchronous generator (PMSG). This machine is in the three phase open end winding configuration and is driven by the dual two-level converter. The two dc-link of the multilevel converter supply two motor drives connected to the final mechanical transmission.**

A new control principle of the generation system is combined to a proper modulation strategy of the dual two-level converter allowing to share the generated power between the two output drives.

The power sharing capability of the generation system satisfies the different power demand from the two output drives.

This architecture can be applied to road vehicles (i.e. buses, urban light truck) where the two wheels are driven by the two motor drives, and to naval ship propulsion systems (i.e leisure craft, work craft) where two propeller shafts are driven by two motor drives. This powertrain configuration can be easily integrated with a battery energy storage system for pure electric operation of the system.

Keywords: hybrid series transmission, multilevel converter, dual two-level inverter,

I. Introduction

The main characteristic of series hybrid powertrains is to have no mechanical couplings between the thermal engine and the output shafts (wheels, propellers). This feature alone makes the series transmissions of a great interest in many terrestrial and marine applications.

For example, the application of such a transmission in urban buses it is foreseeable in order to eliminate the actual mechanical driveline based on an automatic gearbox connected between the thermal engine and the differential gear [1]. By using series hybrid powertrains it is possible to change the collocation of the ICE along the chassis, and by using two wheel motor drives, it is avoided the installation of a differential gearbox. Only these two advantages allow to design new buses with the appreciable features of an increased payload volume and of a lowered floor level. The series hybrid configuration introduces the further advantage of choosing the ICE operating point for any given power in order to reduce fuel consumption and/or exhaust emissions. Under an economical point of view, the cost of the converters and of the electrical machines is almost completely compensated by the avoided cost of the automatic gearbox (initial cost and maintenance cost).

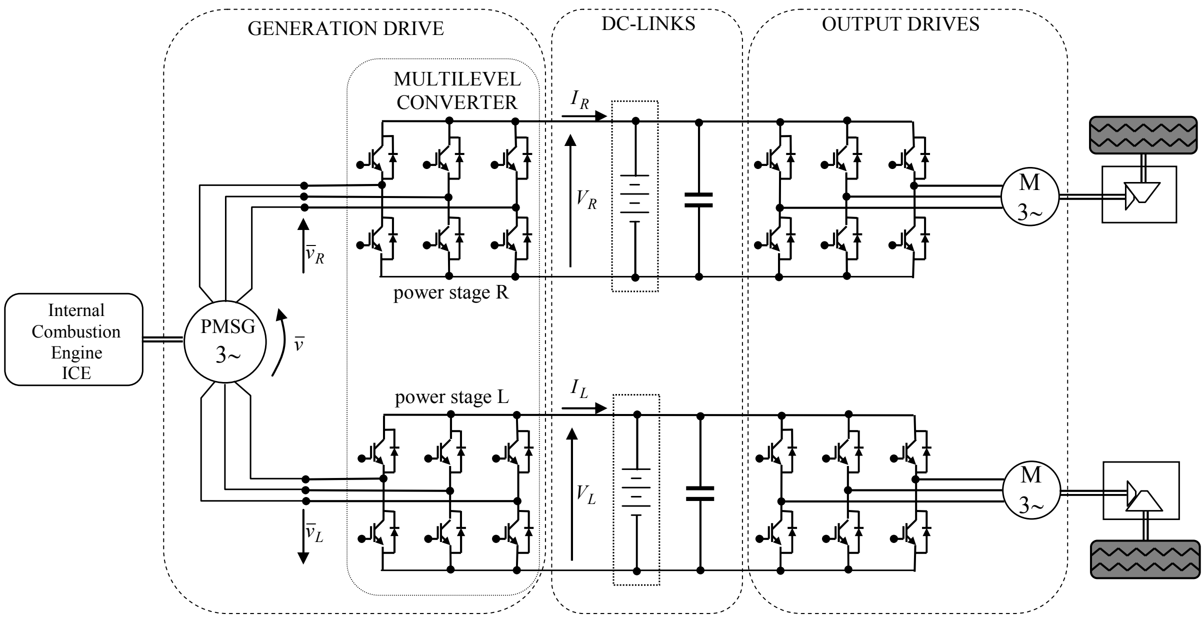

Fig. 1. Electric scheme of the series hybrid transmission

Similar advantages can be expected for marine applications. In particular, the possibility to place the ICE in a different location from the actual stern zone of the hull, it is seen as an important added value of a leisure or a work vessel.

This paper focuses on the configuration and on the control algorithm of the power electronic structure connected between the generation system and the output drives of the series hybrid driveline. Fig. 1 shows a complete scheme of a series hybrid driveline for traction application. In this scheme a direct drive, a PMSG is connected to the output shaft of the ICE. The PMSG is a three phase machine in the open end winding configurations. The six wires of this machine are connected to the six terminals of a multilevel converter in the configuration of a dual two-level inverter. The power stage of this multilevel converter is constituted by two standard, three phase, two level converter. Then, the two electrically separated dc-links supply the two output drives, connected to the right (R) wheel and to the left (L) wheel respectively.

The series hybrid driveline of Fig. 1 can be integrated with an energy storage device based on electrochemical batteries, for pure electric operation or for more flexible hybrid operation of the driveline [2], [3]. Two battery bank can be directly connected to the two dc-link. In this case the dc-link voltages depend on both the battery load and the battery state of charge (SOC) . During pure electric operation, the generation system is switched off, and the two output drives are directly supplied by the two battery banks. During hybrid operation, the generation system can be controlled in order produce the sum of power demanded by the output drive and by the vehicle management unit (VMU), which keeps under control the SOC of the batteries. In this way, the generation system can produce more power than that demanded by the output drives, determining the recharge of the batteries, or less power than that demanded by the output drives determining the discharge of the batteries. With this system, by choosing instant by instant the energy percentage coming from the battery or from the generation system, a very flexible powertrain can be designed for obtaining the best battery energy utilization during an operating mission of the vehicle.

The series hybrid driveline configuration analyzed in this paper does not have any additional energy storage systems, apart of the capacitor bank of the converters. In this basic configuration, the generation system must be controlled in order to produce, instant by instant, the exact amount of power demanded by the output drives. In this way, the control strategy for this configuration is quite complex having stringent requirements with respect to the control of the system with electrochemical batteries.

The proposed hardware structure of the series hybrid driveline is based on the use of four identical power stage, two for the two output drive and two for the multilevel converter connected to the generator. All the four power stages have the same voltage and current ratings. This solution differs from other configurations [1], where the generation power stage is realized by using an inverter with a size double the size of the output drives, yielding to very high cost of this drive.

In other words, the use of the dual two level converter as power stage of the generation drive is an important contribution to the reduction of development, manufacturing and maintenance cost of the hybrid driveline.

The control structure of the system is composed of two level control structure: high level and low level which are detailed described in Section II and III respectively.

The high level control algorithm has the task to generate the reference of the power to be supplied by the generation system. The power demanded by the two drive system depends on the operating conditions of the vehicles (gas pedal, road, steering angle) and cannot be foresight by the control system. For the case with only capacitors connected on the dc-links, the control of the power flow and then the exact balance between generated and absorbed powers is realized through the control of the two dc-link voltages..

The low level control system is represented by the modulation strategy of the multilevel converter which is able to share the generated power between the two side of the converter. Regulation of the power sharing is realized inside a switching cycle, through the control of the voltage applied by the two side of the converter to the generator. This modulation strategy is also fully compliant with the multilevel modulation requirement to synthesize the output voltage by minimizing the voltage.

II. HIGH LEVEL CONTROL ALGORITHM

The control scheme of Fig. 2 shows the high level control algorithm of the series hybrid system. From the right, the control scheme is composed by two control loop for the regulation of the two dc-link voltages. This two loops calculate the reference of electric power P_R^*, P_L^* demanded by the output drives connected to the drive at the right and by the drive at the left, respectively. Neglecting losses, the sum of the power demanded by the two output drive corresponds to the power P_g that should be generated by the generation system. For a given value of P_g there is a unique set of torque and speed values at the engine shaft that optimize the operation of the generation system. Usually, as optimal operating point, is considered the point at minimum fuel specific consumption. The optimal operating point of the engine for any given power must be known and mapped into two look up-tables, giving as output, the output torque and the rotating speed of the ICE. Then, the reference of speed is sent to the ECU, while the reference of torque is sent to the drive of the PMSG [4].

The power electronic stage of the generator drive is constituted by the dual two-level converter [5] - [14]. This converter has the task to split the generated power P_g in the two terms P_{gR}, P_{gL} depending on the power demand coming from the two output drives. The power sharing strategy, embedded in the modulation strategy of the multilevel converter and described in Section III, allows to generate different voltages at the two ac-side of the multilevel converter at each switching cycle [14].

In other words, if $\bar{v}^*$ is the required voltage to be applied to the controlled electric machine for obtaining the desired speed control, $\bar{v}^*$ can be composed as the sum of two desired voltage vector generated by the two ac side of the multilevel converter

$$\bar{v}^* = \bar{v}_R^* + \bar{v}_L^* \tag{1}$$

Being the ac current $\bar{i}$ the same for the two ac side of the converter, $\bar{v}_R^*$ and $\bar{v}_L^*$ are proportional to the power injected into the two dc-link

$$P_g = \bar{v}^* \bar{i} \tag{2}$$

$$P_g = P_{gR} + P_{gL} = \left(\bar{v}_R^* + \bar{v}_L^*\right)\bar{i} \tag{3}$$

On both sides, the dc-link capacitor bank is charged by the difference between the generated power and the power demanded by the output drive. By integrating this power and introducing the value of the installed capacitance, the corresponding dc-link voltages can be calculated.

The outer control loop has the task to control this two dc voltages (V_R, V_L). This loop is based on two PI controllers, having as input, the error between the real value and the reference voltages (V_R^*, V_L^*) of the two dc-links. These dc-link voltage references have the same value and can be kept equal to the rated dc voltage of the system. The outputs of the two PI regulators are the reference of two dc currents (I_R^*, I_L^*) should be generated by the two output of the multilevel converter connected to the generation system.

$$P_g^* = V_R I_R^* + V_L I_L^* \tag{4}$$

By imposing vector $\bar{v}_R^*$ and $\bar{v}_L^*$ lying in the same direction, the two ratios $\bar{v}_R^*/\bar{v}^*$ and $\bar{v}_L^*/\bar{v}^*$ represent the sharing of the total generated power, between the two dc-link. Introducing this assumption in (1) and (4), the power balance equation for the two converter side is

$$\frac{\bar{v}_R^*}{\bar{v}^*} = \frac{V_R I_R^*}{V_R I_R^* + V_L I_L^*} = k \ , \tag{5a}$$

$$\frac{\bar{v}_L^*}{\bar{v}^*} = \frac{V_L I_L^*}{V_R I_R^* + V_L I_L^*} = 1 - k \tag{5b}$$

Parameter k is the power sharing coefficient and represents an input of the modulation strategy of the dual two-level converter described in the Section III.

For the most frequent case, in which the two output inverter have the same voltage rating, it is assumed that $V_R \cong V_L$, and (5) can be further simplified yielding to the following equations for the two reference ac voltages $\bar{v}_R^*$, $\bar{v}_L^*$ of the multilevel converter

$$\bar{v}_R^* \cong \frac{I_R^*}{I_R^* + I_L^*}\bar{v}^* , \tag{6a}$$

$$\bar{v}_L^* \cong \frac{I_L^*}{I_R^* + I_L^*}\bar{v}^* . \tag{6b}$$

These two voltages will be then synthesized at each switching cycle by using the modulation technique described in Section III. In this converter, owing to the dual two level converter characteristics, the inverter reference output voltages $\bar{v}_R^*$, $\bar{v}_L^*$ are also subject to a limitation depending on the dc voltage and the modulation index [14]. The admitted range of voltage $\bar{v}_R^*$ and $\bar{v}_L^*$ is shown in the next Section.

In the control scheme of Fig. 2, with reference to the two dc-link voltage control loop, a feed-forward action can be added in order to better compensate sudden changes in motor drives power demand (I_{FFR}, I_{FFL}). Its utilization depends on the availability of these two current in the control system of the two motor drives.

The control scheme of Fig. 2, can be easily modified in order to accept the installation of two electrochemical battery banks on the two dc-link. In this configuration the high level control algorithm keeps under control the

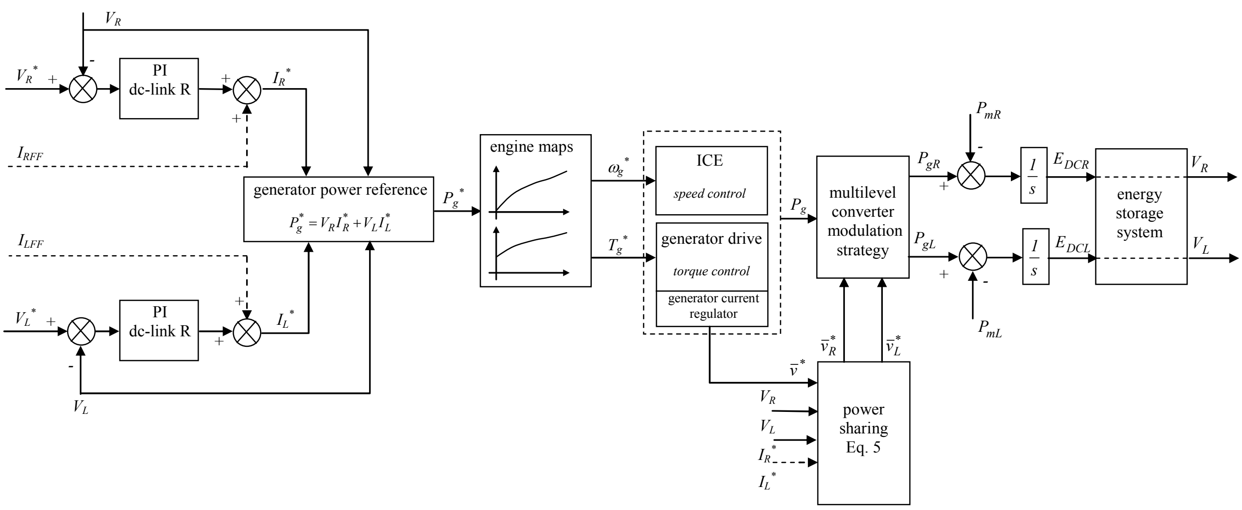

Fig. 2. High level control algorithm of the series hybrid system

current injected into the batteries instead of the controlling the dc-link voltages. In this case, the outer loop represented by the dc-link voltage regulator is substituted by a regulator of the current in the batteries. In this way, the level of voltage of the dc-link depends on both the injected current and the State of Charge (SOC) of the batteries.

III. Modulation Strategy of the Multilevel Converter

This Section deals with the modulation strategy of the dual two-level converter representing the power electronic stage of the generation system as it is shown in the scheme of Fig. 1. In this multilevel converter, by assuming $V_R = V_L = E$, the voltage vectors $\overline{v}_R$ and $\overline{v}_L$ applied to the PMSG by the right side and the left side respectively are given by 18 different output active voltage vectors and one null vector, as represented by the red dots in Fig. 3. By using the SVM technique, these 19 voltage vectors can be modulated to obtain any output voltage vector lying inside the outer hexagon, having a side length of $4/3E$. In particular, with reference to sinusoidal steady state operating conditions, the maximum magnitude of the output voltage vector $\overline{v}^*$, that can be generated by the converter, is $2/\sqrt{3}\,E$ (i.e., the radius of the circle inscribed in the outer hexagon of Fig. 3).

A correct multilevel operation requires the output voltage vector $\overline{v}^*$ to be synthesized by modulating three voltage vectors $\overline{v}_a, \overline{v}_b, \overline{v}_c$, corresponding to the vertices of the triangle in which the output voltage vector $\overline{v}^*$ is located [5].

The output voltage $\overline{v}^*$ can be expressed by means of the duty cycles a,b,c of the three adjacent main vectors as follows:

$$\overline{v}^* = a\,\overline{v}_a + b\,\overline{v}_b + c\,\overline{v}_c\,, \qquad (7)$$

where the duty-cycles a,b,c are given by standard SVM equations.

The two voltage vectors $\overline{v}_R^*$ and $\overline{v}_L^*$, synthesized by the two inverter, are assumed in phase and then lay in the

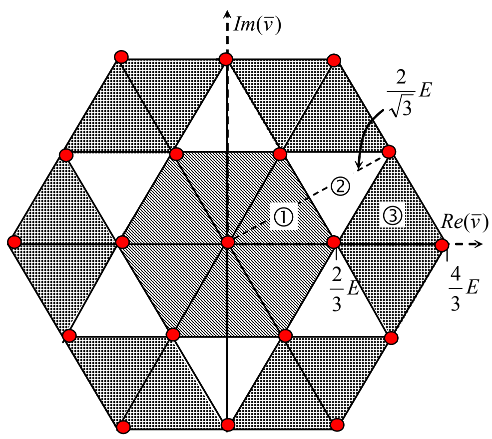

Fig. 3. Highlight of the triangles in the three different regions ①, ②, and ③.

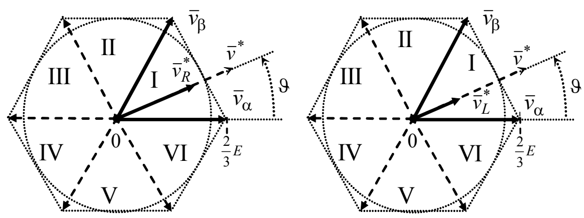

Fig. 4. Reference voltage vectors $\overline{v}_R$ and $\overline{v}_L$ generated by using the same two adjacent active vectors $\overline{v}_\alpha$, $\overline{v}_\beta$.

same sector, as represented in Fig. 4. This assumption allows the two inverters to synthesize $\overline{v}_R^*$ and $\overline{v}_L^*$ by modulating the same adjacent active vectors $\overline{v}_\alpha, \overline{v}_\beta$. As a consequence, the resulting output voltage vectors of the two inverters are:

$$\begin{cases} \overline{v}_R^* = \alpha_H\,\overline{v}_\alpha + \beta_H\,\overline{v}_\beta + \gamma_H\,\overline{0} \\ \overline{v}_L^* = \alpha_L\,\overline{v}_\alpha + \beta_L\overline{v}_\beta + \gamma_L\overline{0} \end{cases}. \qquad (8)$$

In (8) $\alpha_H, \beta_H, \gamma_H$ are the duty cycles of active vectors $\overline{v}_\alpha, \overline{v}_\beta$ and null vector for the right side of the converter, respectively. In the same way, $\alpha_L, \beta_L, \gamma_L$ are the duty cycles of active vectors $\overline{v}_\alpha, \overline{v}_\beta$, and null vector for the left side of the converter, respectively.

Once the duty cycle of the two inverters have been calculated a proper switching sequence must be defined. The main requirements of the switching sequence are the minimization of the number of switch commutations and the application of correct voltage vectors during commutations. In [14] it has been defined a switching sequence complying with these requirement that can be conveniently used for this application.

The constraints on the duty-cycles of the two converter sides, $0 \le \alpha_R, \beta_R, \gamma_R \le 1$ and $0 \le \alpha_L, \beta_L, \gamma_L \le 1$, introduce a limit in the range of variation of the power sharing coefficient k introduced in (5). In particular, the range of variation of k can be expressed as a function of the desired output vector $\overline{v}^*$.

Assuming sinusoidal output voltages $\left(\overline{v}^* = V^* e^{j\vartheta}\right)$ and introducing the modulation index

$$m = V^* \Big/ \frac{2}{\sqrt{3}} E \qquad (0 \le m \le 1) \qquad (9)$$

the admitted values of k are given by

$$\frac{1}{2} - a \;\le\; k \;\le\; \frac{1}{2} + a\,, \qquad (10)$$

where,

$$a = \frac{1-m}{2m}\,. \qquad (11)$$

By means of (10) and (11) the possible values of k can be determined as function of the modulation index m. This relationship is graphically represented in Fig. 5. The dashed area defines the possible values of k and then represents the admissible difference between the power supplied by the two side of the converter. By analyzing Fig. 5 the following considerations can be made.

- $m = 1$. The maximum output voltage is required and it is not possible to regulate the power sharing between the two dc sources. In this case only the value $k = 0.5$ is acceptable, the two power stage of the converter apply the same voltage at the generator and the same power is supplied to the two dc-link.

- $0.5 \le m \le 1$. The coefficient k is limited as function of m, showing an increasing range of variation as m decreases.

- $m < 0.5$. The output voltage vector lies within the circle of radius $E/\sqrt{3}$. In this case, the generated power can be supplied by the two power stage with any ratio. In particular, if k is set to 0, all the generated power is supplied by power stage L, whereas if k is set to 1 all the generated power is supplied by power stage R. This is a very important feature of this converter since it is possible to control the generator by using one inverter only, if necessary.

- $m < 0.5$. The power ratio k could be greater than unity or lower than zero. It means that an amount of power could be transferred from one dc source to the other, and the inverter voltages $\overline{v}_R$ and $\overline{v}_L$ become in phase opposition, as shown by (3). This feature could be interesting when using batteries on the dc-link, because it represents the possibility to transfer energy between the two energy storage systems.

This power sharing limitation of the multilevel converter is fully compliant with the application of converter for the generation system to a series hybrid driveline. In both traction and marine applications, the two output drives demand different value of power only when the output shafts (wheels, propellers) turn at low speed, meaning low output power. Full range regulation of the power sharing coefficient $0 \le k \le 1$ is required only during full steering of the vehicle, that must be allowed only at low speed, corresponding to about 15-20% of the rated driveline power. Increasing of the vehicle speed yields to a reduction of the steering capability and than of the power sharing of the power at the two output drives. The proposed multilevel converter allows full power sharing regulation below 50% of the rated voltage (speed) of the generator and a decreasing regulation capability from 50% to 100% of the rated voltage (speed) of the generator. With this system it is easy to satisfy both power demand and power sharing of this application by coupling the multilevel converter and the generator with a thermal engine which generally is able to generate half the rated power about from 60% of the rated speed.

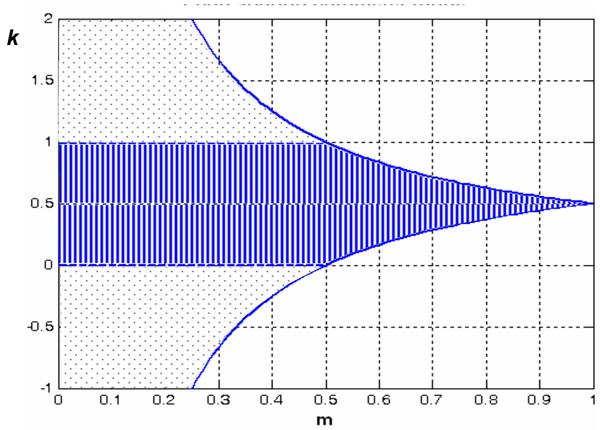

Fig. 5. Limits of power sharing coefficient k vs. modulation index m.

IV. Simulation

The series hybrid powertrain proposed in this paper has been modelled by using the MATLAB-Simulink tools. Two different simulation have been implemented for modelling the high level control algorithm described in Section II and for modelling the multilevel control strategy of the dual two-level converter.

A. High Level Control Scheme

The high level control scheme shown in Fig. 2 is modeled in order to verify the capability of the proposed generation system to supply the traction system in a wide range of operating condition.
This scheme includes the model of the generation system constituted by: ICE, PMSG, drive of the PMSG, control system of the generation unit. The scheme includes also the model of the multilevel converter with reference to its power sharing capability and a simplified model of the load. In the scheme the generation system is assumed to be ideal and no losses are considered in the PMSG and in its drive system. The parameters of the ICE, of the PMSG and of the control scheme of the generation system are given in Tab. I.

TABLE I
PARAMETERS OF THE GENERATION SYSTEM USED IN SIMULATION

Internal Combustion Engine - ICE	
model	MR704A
type	diesel - common rail injection
stroke number	4
rated power	50 [kW]
rated speed	3500 [rpm]
time constant of the engine	80 [ms]
speed regulator K_P	0.1
speed regulator K_I	0.01
Permanent Magnet Synchronous Generator - PMSG	
rated power	55 [kW]
rated speed	3500 [rpm]
rated voltage	400 [V]
torque constant (Kt)	2.05 [Nm/A]
back e.m.f (Ke)	1.15 [Vs^{-1}]
phase resistance	14 [mΩ]
phase inductance	0.6 [mH]
Dual Two Level Inverter	
dc-link capacitance	40 [mF]
dc-link voltage reference	300 [V]
switching frequency	2000 [Hz]

The generation of the electric power by the generation system, is obtained by keeping the ICE at the lowest fuel consumption operating point. This seeking procedure as been performed using test bench results of the considered ICE, given by the engine manufacturer. The operating point of the ICE (torque and speed) at minimum fuel consumption, for any given power, are shown by the diagram of Fig. 6 and are included in the block ‘engine map’ of the control scheme of Fig. 2. Fig. 7 shows the corresponding specific fuel consumption of the ICE for any output power in optimal operating conditions.
The ICE can be easily represented by using the diagram of Fig. 8. In this diagram, at any speed, the output torque is given as a percentage of the maximum torque at that speed. This percentage represents the input command (called ‘gas command’ in Fig. 8) of the Engine Control System. By using test bench results, the dynamic behaviour of the ICE is represented by a first order transfer function with the time constant given in Tab. I. This time constant is introduced between the gas command and output torque.
In the scheme of Fig. 9, the speed and torque references given by the optimal engine operating points (‘engine maps’ of Fig. 6) are addressed to the speed and torque regulator respectively.
The speed regulator generates the ‘gas command’ for the Engine Control Unit of the ICE, while the torque regulator is given by a standard torque/current regulator of the PMSG drive system.
Then, the output of the torque regulator represents the reference output voltage that must be synthesized by the multilevel converter.
The control strategy of the generation system shown in Fig. 9 has been chosen in order to have the fastest dynamic response in the power generation system. It is obtained by exploiting the capability of the electric drive to generate fast varying torque with respect to the dynamic response of the thermal engine.
The control scheme of Fig. 2 is completed by the two output drives, and the two dc-link voltage regulators.

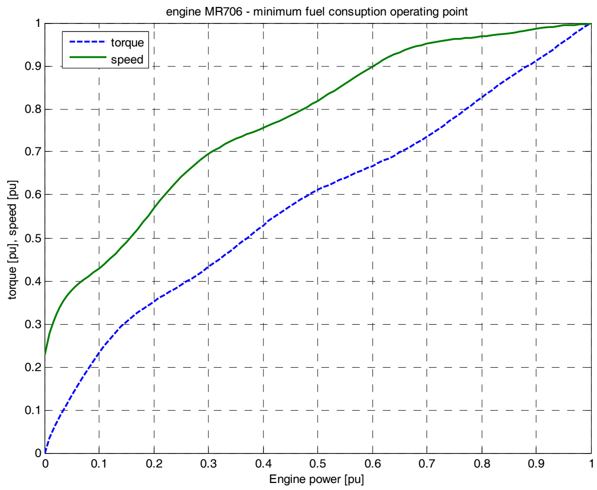

Fig. 6. Engine MR706, torque and speed operating points vs. power at minimum fuel consumption

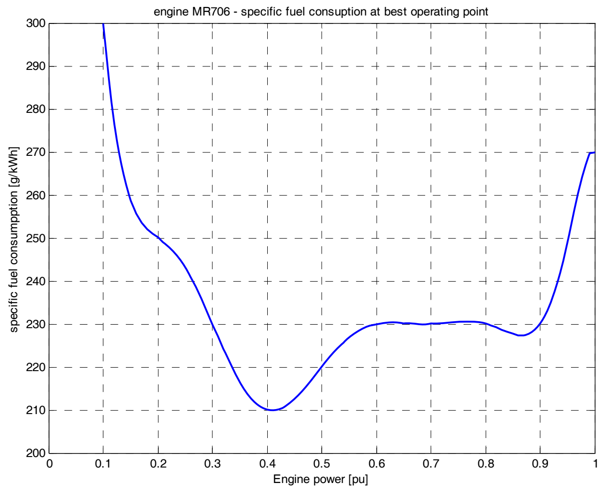

Fig. 7. Engine MR706 Specific fuel consumption at the best operating point

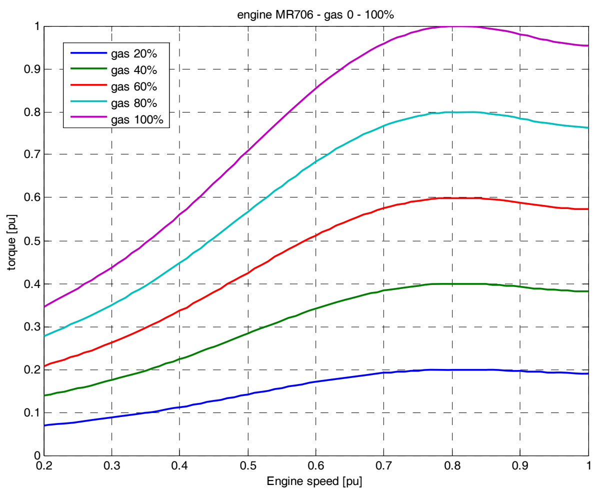

Fig. 8. Control scheme of the variable speed generation system

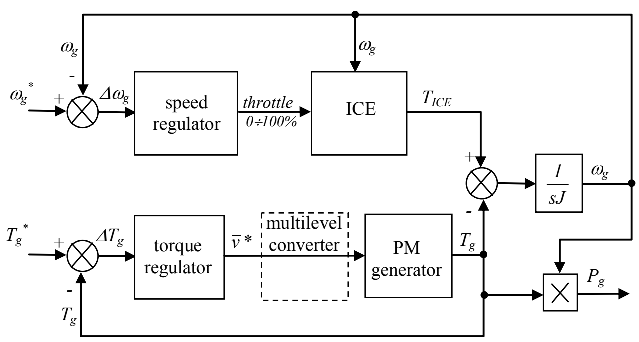

Fig. 9. Engine MR706 Torque output vs. speed. Throttle 0-100% as parameter

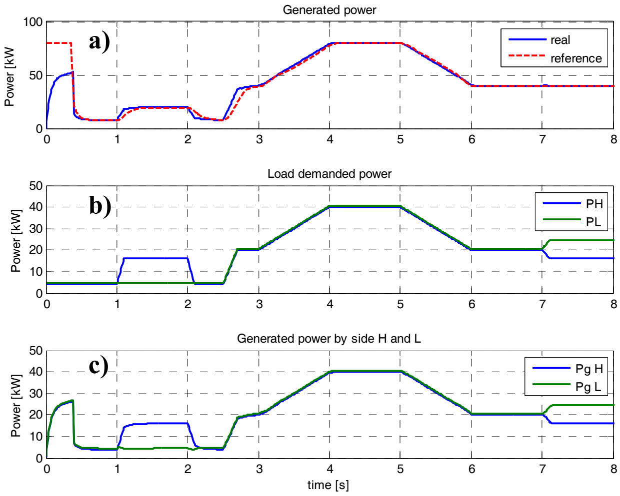

Fig. 10. Power. a) generated by the generation system; b) demanded by output drive R and L; c) supplied to drive R and L

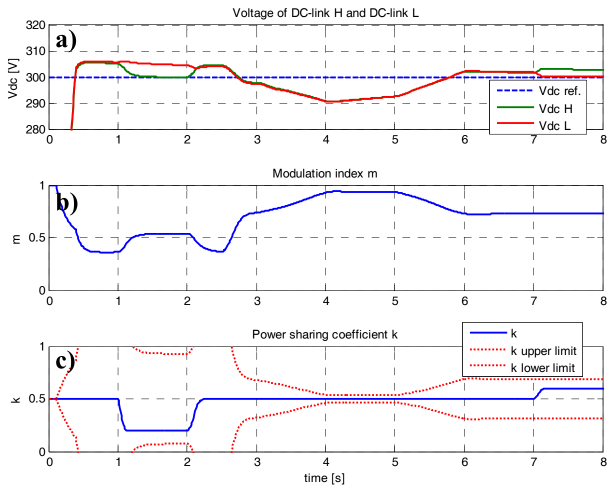

Fig. 11. a) dc-link voltage, b) modulation index, c) power sharing coefficient

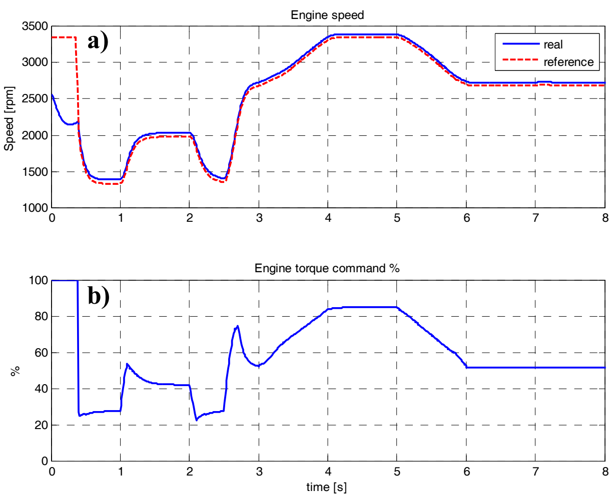

Fig. 12. a) ICE speed; b) ICE torque

The output drives are represented with the two disturbance signals: load power P_R, P_L, acting on the two dc-link voltage loop. The values and the dynamic behaviour of these two powers depends on the load characteristic and will be discussed further. The two dc-link regulators have been tuned in order to keep the voltage variation of the dc-link during the fastest load variation below 5% of the rated dc-link voltage.

Simulation results have been given in Figs. 10-13 representing the behaviour of the system in transient and steady state conditions, referred to the following manoeuvrings of a road vehicle.

The ICE is started at no load, then the generation system is operated and the two dc link voltage are set to the reference voltage in 0.5s, while the load power demand P_R, P_L, is kept low. At the instant 1*s* the two output drives demand different power representing a low speed manoeuvring, where the left wheel the drive L is the outer wheel. In this condition the generation system supplies the total amount of power (20kW) required by the output drives, which is shared between the two dc-links with a power sharing coefficient of about k=0.25 meaning 5kW at the right side and 15kW at the left side.

In the time interval from 3*s* to 6*s* the total power demand rises up to 80kW. In this case the same power flow is established in the two side of the drive system, meaning a power sharing coefficient k=0.5. This case represents an acceleration transient of the vehicle carried out on a straight path. In the time interval from 6*s* to 7*s* the power demand is constant and equals to 40kW with k=0.5. This case represents operation of the vehicle at constant speed, and straight path.

After time instant 7*s*, the whole power demand is still 40kW, while the power sharing coefficient changes from k=0.5 to k=0.6. This case represents the operation of the vehicle during a turn at constant speed, where the right wheel is at the outer.

Fig. 10a shows the reference and the real value of the whole electric power generated by the generation system. Fig. 10b shows the demanded power from the two output drives due to the operating condition of the vehicle. Fig. 10c shows the power supplied by the two side of the generation system.

Fig. 11a shows the dc-link voltage reference, which is kept to 300V for both the side of the multilevel converter, and the real values of the two dc-link voltages V_{dcR} and V_{dcL}. The parameter of the two dc-link regulators are tuned in order to keep these voltages quite close to their reference, both in transient and in steady state conditions.

Fig. 11b shows the modulation index m, calculated by the drive of the PMSG and sent to the multilevel modulating control system. In Fig. 11c is given the power sharing coefficient k and the limits of variation of this coefficient as a function of the modulation index m as given by (10). The demanded variation of the power sharing coefficient is always inside this band, allowing a correct synthesis of the voltage across the two output side of the multilevel converter.

Fig. 12 shows the dynamic behaviour of the ICE, controlled by the speed control system shown in the scheme of Fig. 9. Fig. 12a shows the reference value and the real value of the engine speed in rpm. Fig.12b shows the required torque command in percentage of the maximum available torque for the given speed.

B. Dual Two-Level Converter

The power stage of the generation drive, given by the dual two level converter, has been tested in order to verify the capability of the modulation strategy to generate the output reference voltage with a given power sharing coefficient as it is described in Section III.

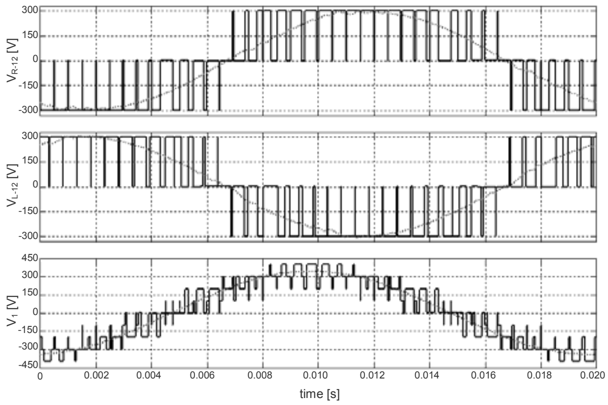

Fig. 13 Dual two-level converter voltage for m = **1**, ***k*** **= 1/2**
a) line to line voltage at the right side b) line to line voltage at the left side c) phase voltage applied to the generator.

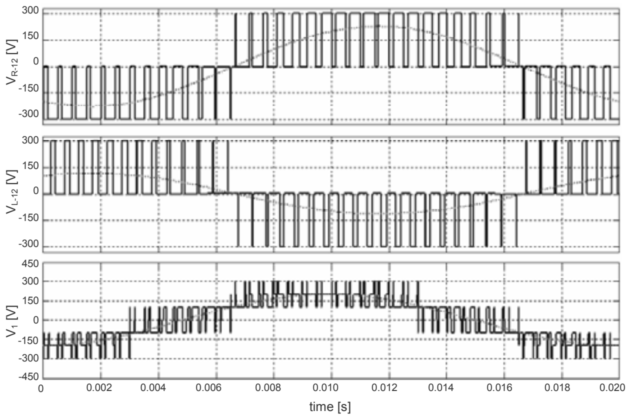

Fig. 14 Dual two-level converter voltage for **m = 1/√3, *k* = 2/3**
a) line to line voltage at the right side b) line to line voltage at the left side c) phase voltage applied to the generator.

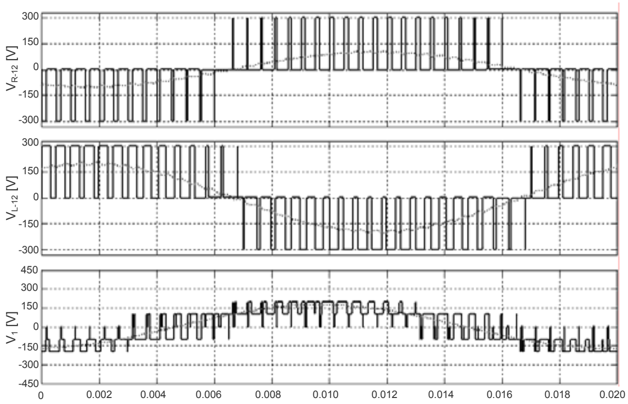

Fig. 15 Dual two-level converter voltage for **m = 1/2** , ***k*** **= 1/3**
a) line to line voltage at the right side b) line to line voltage at the left side c) phase voltage applied to the generator.

Figs.13-15 represent the ac voltage generated by the dual two-level converter. In these diagrams the instantaneous value and the filtered value of voltage are both reported. During this simulations, the switching frequency of the dual two-level converter is kept very low (2kHz) in order to clearly show all the voltage level generated over a fundamental period of the ac voltage.

Fig. 13 is related to the condition of maximum value of the modulation index m = 1 (i.e. $v = 2/\sqrt{3}\ E$), and k = 1/2. Fig. 13a) and 13b), illustrate the line-to-line voltage generated by the right and left side of the dual two-level converter respectively. Fig. 13c) represents the phase voltage applied to the PMSG. In this case, the two inverters generate the same voltages, supplying the same power to the load. It can be noted that the phase voltage is distributed on nine levels.

Fig. 14 shows the same voltage waveforms as in Fig. 13 with $m = 1/\sqrt{3}$ (i.e. $v = 2/3\ E$), and k = 2/3. This value of m corresponds to the maximum output voltage vector that can be generated inside the inner hexagon of Fig. 3. In this case, the outer triangles (region ③) are not involved, and the phase voltage is distributed on the lower seven levels only. Being k = 2/3, the voltage generated by inverter R is twice the voltage generated by inverter L.

Fig. 15 shows the same waveforms as in Fig. 13 with m = 1/2 (i.e. $v = 1/\sqrt{3}\ E$), and k = 1/3. In this case, the locus of the output voltage vector is the circle inscribed in the inner hexagon of Fig.3. Then, the phase voltage is distributed on the lower five levels since only the triangles in region ① are involved. Being k = 1/3, the voltage generated by inverter R is half the voltage generated by inverter L.

The correct multilevel operation of this modulation strategy is proved by observing that in all cases shown in Figs. 13c, 14c, 15c, the phase voltage applied to the PMSG is distributed, in each switching period, on the three levels closest to the synthesized voltage. These voltage levels, in the diagram of Fig.3, correspond to the application of the three voltage vectors on the vertices of the triangle where is located the synthesized output vector.

V. Experimental Results

A full scale size prototype of the dual two-level converter, which is proposed as power stage for the generation system of the series hybrid powertrain, has been realized. The switching control strategy described in Section III has been implemented and experimental test have been carried out in order to confirm the simulation results shown in Section IV-a. Fig. 16 shows a picture of

TABLE II
DATA OF THE DUAL TWO-LEVEL CONVERTER

model	CE450200-DUAL
max. operating dc-voltage	450 [V]
ac rated current	200 [A]
rated power	100 [kW]
switching frequency	7500 [Hz]

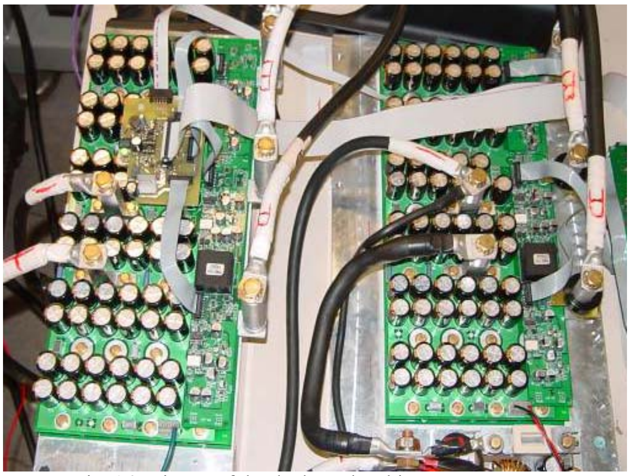

Fig. 16. Picture of the dual two level inverter prototype.

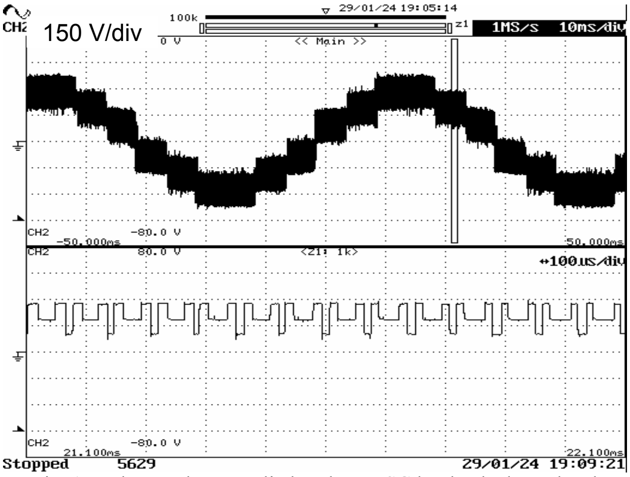

Fig. 17. Phase voltage applied to the PMSG by the dual two-level converter for **m = 1**, ***k*** **= 1/2**

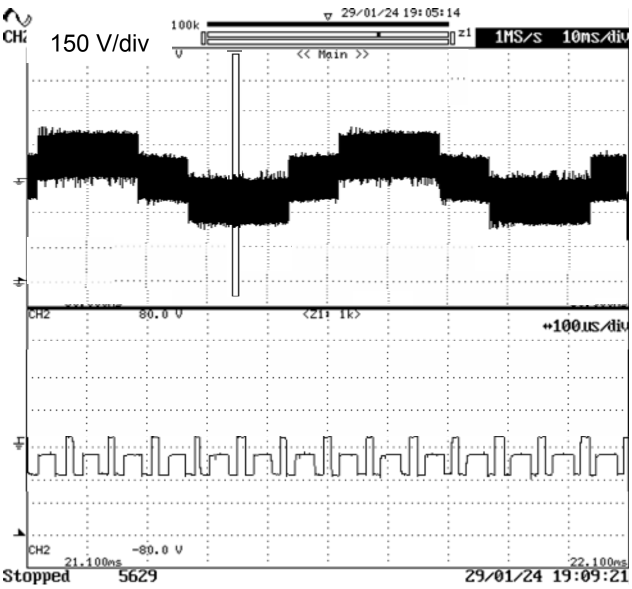

Fig. 18. Phase voltage applied to the PMSG by the dual two-level converter for ***m*** **= 1/2,** ***k*** **= 2/3**

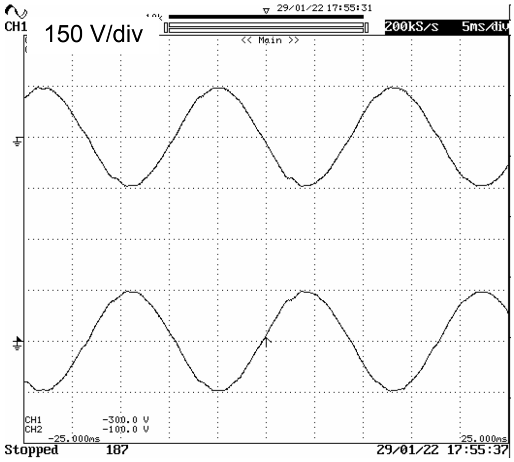

Fig. 19. Filtered line to line voltage generated by the dual two-level converter at the right side (top) and at the left side (bottom), m=1/2, k = 1/2 (balanced)

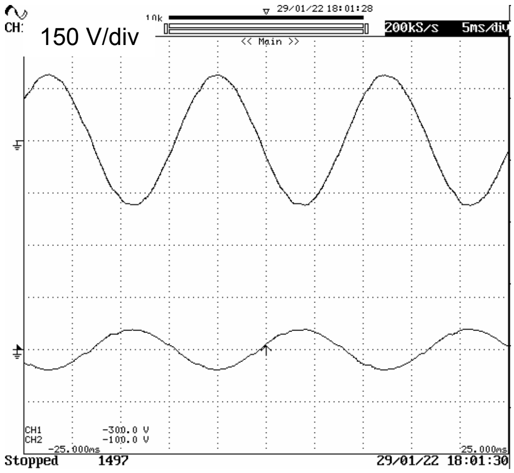

Fig. 20. Filtered line to line voltage generated by the dual two-level converter at the right (top) side and at the left (bottom) side, m=1/2, *k* = 3/4 (unbalanced)

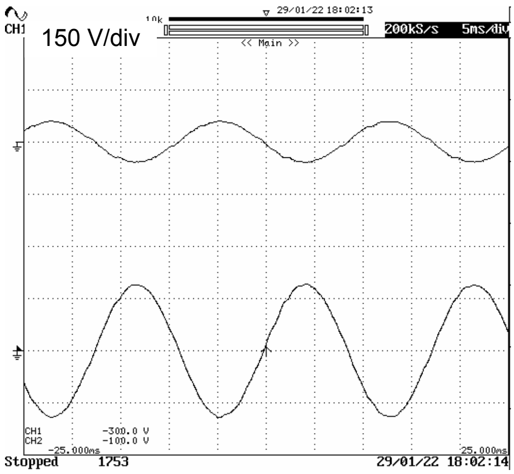

Fig. 21. Filtered line to line voltage generated by the dual two-level converter at the right (top) side and at the left (bottom) side, m=1/2, *k* = 1/4 (unbalanced)

the power stage of the dual two-level converter and Table II illustrate the main data of the power stage.

The modulation strategy discussed in Section III has been implemented on the TMS320F2812® DSP, operating with a clock frequency of 150 MHz, and using both the two independent three-phase PWM generators having a carrier frequency of 10 kHz. In this way, no additional control hardware (e.g., FPGA) is used beside the DSP for the control of the switch commutations.

Fig. 17 shows the phase voltage applied to the machine by the dual two level converter in the case of a modulation index m=0.8. In this case the output phase voltage is distributed on nine levels, since the triangles in region ② and ③ of the diagram of Fig. 3 are involved for the modulation of the output voltages.

Fig. 18 shows the phase voltage applied to the machine by the dual two level converter in the case of a modulation index m=0.4. In this case the output phase voltage is distributed on five levels only, since the synthesized voltage vector is located inside the inner hexagon (region ① of the diagram of Fig. 3).

The power balancing capability of the dual two-level converter is investigated by analyzing the averaged line-to-line output voltages at the left and right side of the converter.

Fig. 19 shows the results obtained with m=1/2 and k = 1/2. In this case, the two line-to-line voltages generated at the two side of the converter have the same amplitude and are in phase opposition. The power delivered by the two side is the same.

Fig. 20 shows the results obtained with m=1/2 and k = 3/4. In this case, the line-to-line voltages generated at the right side is three times greater the voltage generated at the left side. Fig. 21 shows the results obtained with m=1/2 and k = 1/4. In this case, the line-to-line voltages generated at the left side is three times greater than the voltage generated at the right side.

The corresponding power delivered by the dual two-level converter to the two dc-link is unbalanced as the ac-voltages.

The phase voltages and line to line voltages obtained with the prototype of the dual two-level converter show the effectiveness of the proposed control strategy in terms of both correct multilevel modulation and power sharing capability.

VI. CONCLUSION

A new configuration for a series hybrid powertrain is proposed in the paper. This solution is related to the use of a single generation unit and two output drives (wheels, propellers). The generation unit is constituted by an ICE connected to a PMSG. The generator is a three-phase, open-end winding machine driven by a dual two-level converter which allows to split the generated power towards two distinct dc-links.

The paper presents a high level control scheme which keeps under control the two dc-link voltages through the generation of appropriate reference for the ICE control system and for the PMSG drive system. This control algorithm is also able to manage different values of power at the two side of the generation unit, satisfying the different power demand by the two output drives.

The paper points up on the principle of operation of the dual two-level converter used in the generation system and, in particular, deals with the capability of the system to regulate the power sharing between the two side of the converter and to operate a correct multilevel modulation. The limits of the degree of unbalance has been also determined as function of the modulation index.

Simulation and experimental results demonstrate the capability of the proposed generation system and of its control scheme to operate the powertrain in many steady state and transient condition related to the operation of the system as a driveline for a terrestrial vehicle. Being the requirements of a ship propulsion system quite similar to those examined in the paper, this generation system could be also conveniently applied to marine propulsion systems.

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