Model and Control of the Isolated Multi-Modular Converter

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***Abstract*—Multi-modular converters have proven to be one of the most suitable topology to be used in high and power applications. The modularity of these configurations offer several advantages, such as: high quality voltage, redundancy and high efficiency. In these converters, the series connection of modules increase the number of voltage levels, but also the floating voltage of modules with respect the neutral point connection which may give rise to isolation issues at the DC side. Because of this, modules with two or more conversion stages are used to provide isolation and to prevent high floating voltages. However, increasing the number of conversion stages, increase also the losses and the implementation costs. In order to overcome these drawbacks, a new configuration of multi-modular converter is proposed in this paper. The proposed converter provides isolation with one conversion stage by means of using low frequency transformers in each module. The main principle behind this concept, the control structure and simulation results are presented to validate the proposed configuration.**

***Index Terms*—High voltage systems, Isolated Multi-Modular Converter, Modular Multilevel Converter.**

I. Introduction

Multilevel converters have become an attractive configuration due to the fact that high power generation systems operate at high voltage levels. The features that these converters are able to provide, such as high power quality levels, reduced harmonic distortion and reduction of filtering requirements [1] are better if they are compared with two level converters, which require larger filter and redundant switches to reach the same voltage and current requirements [2]. Multilevel converters are used in a wide range of sectors, as for instance: medium voltage drives, static synchronous compensator, active power filters, renewable energy, battery energy stored, high voltage transmission systems among others [3].

A subfamily of multilevel converters are the multi-cells or multi-modular converters, which are formed by a series connection of modules in order to provide: high voltage levels, high degree of modularity, low switching frequency and reduced semiconductor stress. Two of these topologies which are commonly used in high voltage applications are the Cascade H-Bridge Converter (CHB)[4] and the Modular Multilevel Converter (MMC) [5]. The CHB is composed of a series connection H-Bridge modules that provides a high number of output voltage levels. This converter can be found in single or three phase configurations and each module is connected to an external DC source or a passive capacitor component to store energy. In the literature several strategies have been proposed to control the CHB. Some of them are based on the DC voltage control balance [6], which control the power unbalance as a result of difference DC voltage levels [6], while others implement different modulation strategies to reduce the switching frequency and operate in fault mode [7]. Unlike the CHB, the MMC is composed of two series of modules. The modules usually have a half bridge configuration which generates zero and positive voltage levels, so an inevitable DC current flows through the modules. On the other hand, a module based on the full bridge can generate negative, zero and positive voltage levels, thus they operate with positive and negative currents. The series connection of modules are called upper and lower arm, and both are connected through a couple inductance to smooth the current ripple. Moreover, the positive bus bar of the upper arm and the negative bus bar of the lower arm generate a high DC voltage which is mainly used in High Voltage Direct Current (HVDC) applications [8].

Nevertheless, the classical configuration of CHB converters or MMC do not provide isolation between modules. Therefore, when several modules are necessary in order to operate at high voltage levels, there are some application where they can not be used as the floating voltage in modules go over the admissible limits. For this reason, modules with two stages of conversion are used to provide isolation and thus avoid floating voltages. In most of the cases a DC-DC stage with a high frequency transformer is added in each module to solve this problem [9] -[10]. However, adding more components in the converter, give rise to higher losses and increase the implementation costs. Another solution proposed is the use of Power Electronics Transformer (PET), also known as Solid-State Transformer [11], which has a high power density and two or more conversion stages. Between these configurations a high or medium frequency transformer is used to isolate the low voltage side from the medium or high voltage side. However, the increase of conversion stages in the PET also increase the implementation costs.

In this paper a new configuration of converter able to deal with the high floating voltage problem by using isolated modules is proposed. The proposed converter called Isolated Multi-Modular Converter (IMMC) has two arms connected

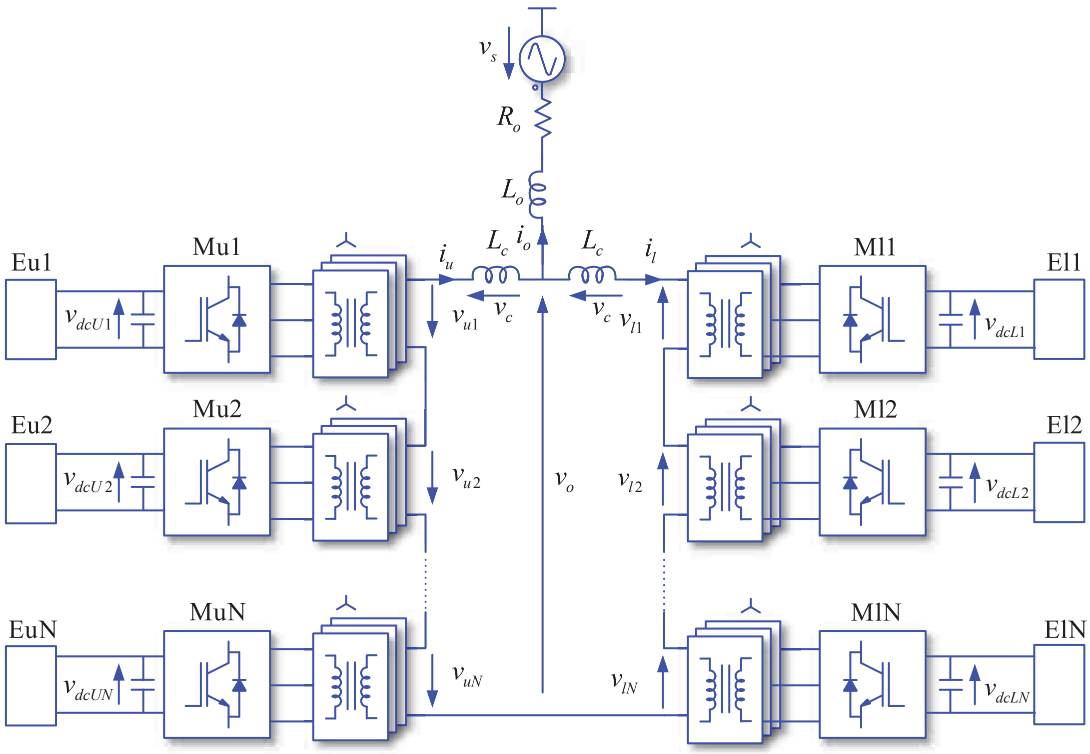

Fig. 1. Isolated Multi-Modular Converter (IMMC)

in parallel and each of them are composed of N modules in series connected through low frequency transformers. The transformers provide isolation between the high AC voltage and the DC side of each module with one conversion stage. To validate this proposal, a study case of a three phase converter with three modules connected in series per arm are used. The nominal power is 6MW and the grid voltage 2.5kV/50Hz. Nevertheless, it is possible to increase the number of modules to obtain higher voltage levels.

II. Isolated Multi-Modular Converter

The configuration of the IMMC is shown in Fig.1. The converter has two arms with N modules connected in series through low frequency transformers which provide isolation to the module. An external DC source is connected to the DC side of the module, while the low frequency transformer is connected to the AC side. The single phase IMMC is composed of modules with a full bridge converter connected to a single phase transformer, where the primary winding is connected to the converter side and the secondary winding to the next module in the arm. In case of the three phase IMMC, the modules consist of a full bridge or a two level three phase converter, the criteria for selecting one or another is based on the DC and the AC requirements. Modules with full bridge converters have one DC source per module and each phase has the same configuration of the single phase converter. However, two more phases with the output voltage lagged 120 are required to generate the three phases. On the other hand, the three phase module is connected through a three phase transformer with a wye configuration in the primary side and with free access to the secondary side to connect the modules in series. Fig.2 shows the single and the three phase module.

The arms are connected in parallel between the coupling inductances, which are responsible for reducing the current ripple due to the switching voltage generated by the modules. Since the coupling inductance is in series with the stray inductance of the secondary winding in the transformer as the number of modules increase, the equivalent stray inductance increase as well and thus, it is possible to reduce the coupling inductance according to the current ripple required in the arms.

III. Dynamic Model

The dynamic model of the converter is analyzed through the equivalent circuit depicted in Fig.3, where the modules are represented as a voltage source controlled by means of a modulated DC source. In this figure, the equivalent stray inductance at the secondary side of the transformers, together with the coupling inductance of each arm is modeled through an equivalent inductance connected in series with a resistance which emulates the power losses. The AC system is composed of a passive inductance with a resistance to represent the output filter and the step-up transformer connected to the AC grid.

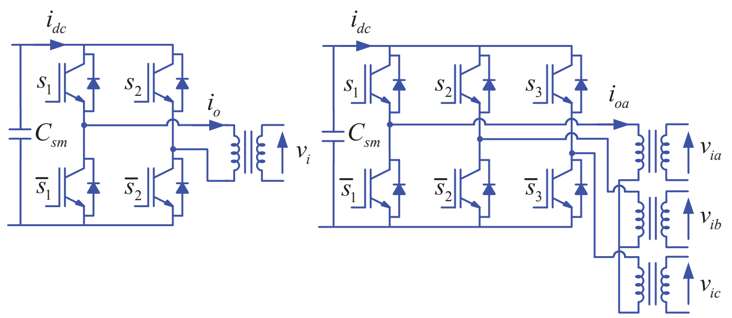

Fig. 2. Single and Three-phase module

The equations that describe the model are valid for single and the three phase converters, as the main difference between both configurations lays on the control strategy required to balance the power flow between phases.

As it was mentioned before, each module is modeled as a voltage source controller where its value is given by:

$$v_{i,k} = \frac{V_{dc\_i,k}}{2} m_{i,k} \tag{1}$$

Where $m_{i,k}$ is the modulation index of the module $k = \{1, .., n\}$ in the arm $i = \{\text{up, low}\}$ and $V_{dc\_i,k}$ the DC source of the module k. The voltage generated by the series connection of all modules give rise to the voltage of each arm, which can be written as:

$$v_i = \sum_{k=1}^{n} v_{i,k} \tag{2}$$

The modules can operate with similar or different DC voltage levels. However, the minimum admissible voltage for controlling the power injected into the grid is limited by the grid-side voltage amplitude. Considering that all modules operate at the same DC voltage level, the output voltage defined in (2) can be rewritten as:

$$v_i = \frac{V_{dc}}{2} \sum_{k=1}^{n} m_{i,k} = \frac{V_{dc} N}{2} m_i \tag{3}$$

Where N is the number of modules per arm and m_i is the equivalent modulation index. According to the current vectors defined in Fig.3, the current arm can be decomposed into the output current, which is used to control the power transferred from the modules to the AC system, and the circulating current which is responsible of controlling the voltage variation between both arms. The circulating current flows through the arms without having any influence in the AC side of the converter. Therefore, it is possible to decouple each current and control both of them independently. Considering the information mentioned before, the upper and the lower current arm are defined by (4), where i_o is the output current and i_c the circulating current.

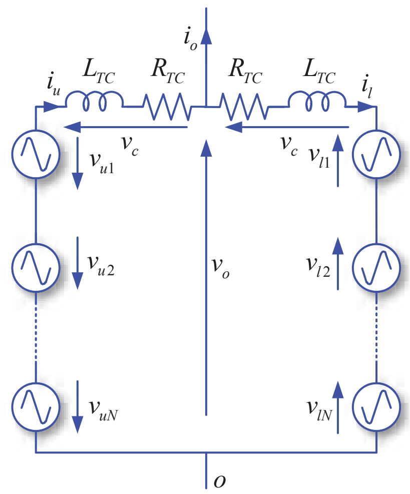

Fig. 3. Equivalent circuit of the IMMC

$$i_{up} = \frac{i_o}{2} + i_c \tag{4a}$$

$$i_{low} = -\frac{i_o}{2} + i_c \tag{4b}$$

In order to define the model of the IMMC, one phase of the converter will be analyzed. Bearing in mind the equivalent model shown in Fig.3, the dynamic equations that represents the upper and the lower arm are:

$$R_{TC} i_{up} + L_{TC} \frac{di_{up}}{dt} = -v_{up} - v_o \tag{5a}$$

$$R_{TC} i_{low} + L_{TC} \frac{di_{low}}{dt} = v_o - v_{low} \tag{5b}$$

Where R_{TC} is the equivalent arm resistance, L_{TC} is the equivalent arm inductance and v_o is the output voltage of the converter. This voltage is measured between the coupled inductance and the connection point o, and its value depends on the upper and the lower current arm variation. In the following equation, another way of representing the dynamic model presented above is shown. In this case, the output and the circulating current are used.

$$\frac{R_{TC}}{2} i_o + \frac{L_{TC}}{2} \frac{di_o}{dt} = \underbrace{\frac{-v_{up} + v_{low}}{2}}_{v_t} - v_o \tag{6a}$$

$$Ri_c + L\frac{di_c}{dt} = -\underbrace{\frac{(v_{up} + v_{low})}{2}}_{v_c} \tag{6b}$$

Where v_t represents the output voltage and v_c is the voltage drop of the equivalent inductance. Replacing both variables in the right side of the equation (6a) and (6b), it is possible to obtain the upper and the lower voltage arm.

$$v_{up} = v_c - v_t \tag{7a}$$

$$v_{low} = v_c + v_t \tag{7b}$$

The power injected into the grid depends on the total power generated by all modules. Neglecting the losses in the converter, the power balance of the upper and the lower arm is determined according to the power generated and the variation of the stored energy by means of:

$$\sum_{k=1}^{n} P_{i,k} = \sum_{k=1}^{n} P_{e\_i,k} - \underbrace{\frac{d}{dt} \sum_{k=1}^{n} \frac{C_{sm}}{2} V_{dc^2\_i,k}}_{P_{sm}} \tag{8}$$

Where $P_{i,k}$ is the output power of the module k in the arm i, $P_{e\_i,k}$ the power generated by the DC source and P_{sm} the variation of the energy stored in the capacitor C_{sm} of the module k. The variation of the energy stored can be rewritten using the average DC voltage of all modules in one arm. The expression is given by:

$$\frac{d}{dt} \sum_{k=1}^{n} \frac{C_{sm}}{2} V_{dc^2\_i,k} = \frac{d}{dt} \sum_{k=1}^{n} \frac{C_{sm}}{2} \left(\frac{\overline{V}_{dc\_i,k}}{N} \right)^2 \tag{9}$$

$$= \frac{C_{sm}}{2N} \frac{d}{dt} \overline{V}^2_{dc\_i}$$

Using the dq frame transformation and assuming that the converter operates at unity power factor ($v_{sq} \simeq 0$), the output power of each modules is represented as:

$$P_{i,k} = \frac{3}{2} v_{d\_i,k} i_{d\_i} \tag{10a}$$

$$Q_{i,k} = -\frac{3}{2} v_{d\_i,k} i_{q\_i} \tag{10b}$$

The power generated by the upper and the lower arm set the output and the circulating current references. Considering the equation presented in (10) and the output voltage of the upper and the lower arm, it is possible to obtain the relation between the power balance and the dynamic model of the IMMC. The total power generated by both arms is given by:

$$P^{\Sigma} = \sum_{k=1}^{n} P_{up,k} + \sum_{k=1}^{n} P_{low,k} \tag{11}$$

$$= \frac{3}{2} v_{sd} (i_{d\_low} - i_{q\_up})$$

The equation (11) considers that v_{low} is in phase with the grid, and v_{up} is lagged 180 according to the voltage arm defined in Fig.3. Neglecting the voltage drop in the equivalence inductance, the d component of $v_{d\_up} = -v_{sd}$ and $v_{d\_low} = v_{sd}$. Using the equation (4) and (11), it is possible to define the output current as:

$$i_{od} = -\frac{2P^{\Sigma}}{3v_{sd}} \tag{12}$$

Furthermore, the power difference between the arms is used to generate the circulating current required to compensate the power unbalance. Considering the same assumption mentioned before, the power difference is defined by:

$$P^{\Delta} = \sum_{k}^{n} P_{upk} - \sum_{k}^{n} P_{lowk} \tag{13}$$

$$= -\frac{3}{2} v_{sd} (i_{d\_up} + i_{d\_low})$$

Therefore, the d component of the circulating current is:

$$i_{cd} = -\frac{P^{\Delta}}{3v_{sd}} \tag{14}$$

The q component of the output and the circulating current depend on the reactive power control.

IV. Control Method

Two independent control are implemented in the IMMC. The first control called centralized controller is responsible for managing the power injected into the grid and controlling the circulating current to compensate the power unbalance presented between the arms. The second control called local controller is integrated in each module and its purpose is to adapt the modulation index sent by the centralize controller in order to control each DC voltage independently. The following subsections describe both controller in detail.

A. *Centralized Controller*

The left side of Fig.4 shows the centralize controller. The structure is composed of two current control loops which are in charge of controlling the output and the circulating current. The d component of the output current reference is set by an external power loop, which controls the average voltage in both arms. On the other hand, the q component is set by the

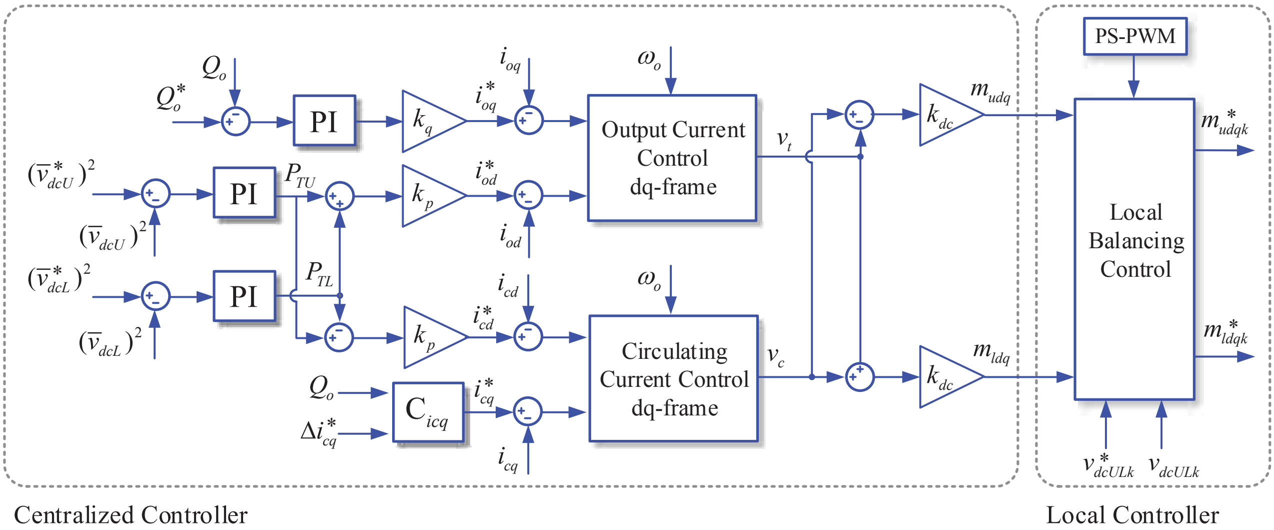

Fig. 4. Control of the IMMC

reactive power loop whose value can be defined to support the grid voltage.

In the circulating current control, the reference of the d component is defined by the active power difference between the arms. In such a way, the current that flows through the arms compensates the power unbalance to control the average voltage close to the reference. The q component is defined by the reactive power injected into the grid and the current Δi_{cq}, which is set by the maximum power difference supported among modules of one arm.

The output and the circulating current control are built using the dynamic model of the IMMC defined in (6), where their output voltages v_t and v_c are used to generate the upper and the lower voltage references and subsequently the general modulation index.

B. *Local Controller*

Before sending the modulation index to each module, the local control adjusts the signals according to the voltage references. There are two possible scenarios which have been considered. In the first case, all modules operate at the same DC voltage and thus the output voltage of the arm have symmetrical levels. In the second case, the modules operate at different DC voltage levels, this situation could happen when solar panels are used as external DC sources. Since the voltage in the PV panels varies with solar radiation and temperature, if all modules operate at their maximum power, partial shading and power mismatching can result in different levels of power generation. These power variations are also observed in the DC voltages.

The series connection cause that all modules of one arm have the same current flowing through them. However, there are some cases where modules can not provide the same power, therefore their DC voltages can increase or decrease depending on the current level. For this reason, the local controller has a voltage control loop which modify the d and the q components of the modulation index in order to provide the capability of changing the DC voltage level.

V. Simulation Results

In order to validate the IMMC, simulation results are presented. The configuration has three modules per arm with two-level three phase converters. In this study case, each module has a DC voltage of 1.5kV and a rated power of 1MW. Considering the total number of modules, the nominal power of the IMMC is 6MW and the grid voltage is 2.5kV. Other parameters of the system are presented in table I.

Two different test are done to validate the functionality of the converter. In the first case, the dynamic and the steady state performance of the IMMC is analyzed by means of a power change in all modules of the upper arm, while modules in the lower arm do not generate power. All modules have the same power change and their variation take place at 0.1s from 0 to 1MW. In the second test, both arms operate at nominal power, when suddenly two power changes happen. These power variations occurs in the first module of the

TABLE I
Simulation Parameters

Parameters	Symbol	Value
Nominal Power	P_o	6MW
Grid Voltage	v_s	2.2kV
Frequency	f_s	50Hz
Number of modules per arm	N	3
DC voltage in each module	v_{dc}	1.5kV
Power of each DC source	$P_{i,k}$	1MW
Coupling Inductance	L_c	0.1mH
Arm Resistance	R_c	0.00001Ω

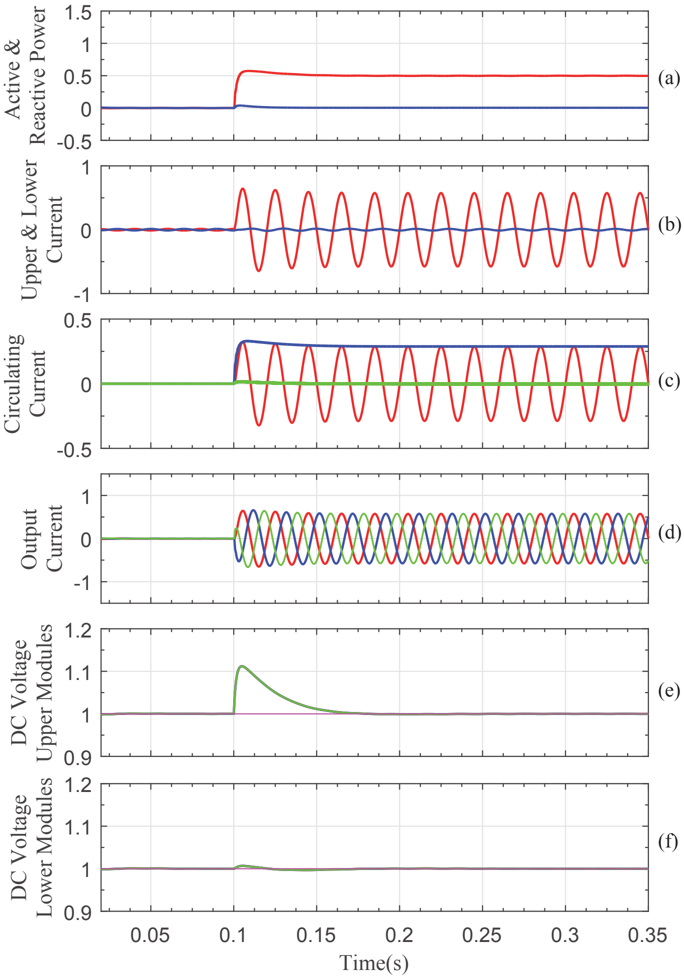

Fig. 5. Dynamic performance of the IMMC with a power variation at 0.1s in all modules of the upper arm. (a) Output power, (b) Upper and lower current, (c) Circulating current in the dq frame and circulating current in phase a, (d) Output current in abc, (e) DC voltage of all modules in the upper arm, (f) DC voltage of all modules in the lower arm.

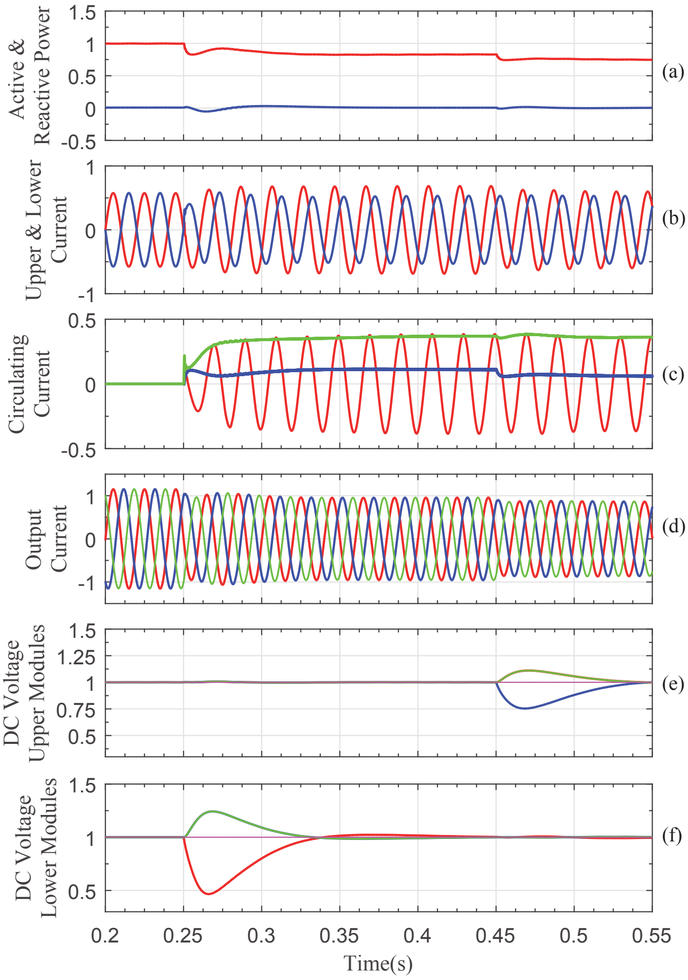

Fig. 6. Dynamic performance of the IMMC with a power variation at 0.25s in the first module of the lower arm and at 0.45s in the second module of the upper arm. (a) Output power, (b) Upper and lower current, (c) Circulating current in the dq frame and circulating current in phase a, (d) Output current in abc, (e) DC voltage of all modules in the upper arm, (f) DC voltage of all modules in the lower arm.

lower arm at 0.25s and in the second module of the upper arm at 0.45s, their power change from 1MW to 0MW and 1MW to 0.5MW respectively. The test presented are done to validate the converter in nominal and power imbalance operation. Simulation results described above are shown in Fig.5 to Fig.7 in per unit system.

The result of the first test are shown in Fig.5. The power injected into the grid is shown in Fig.5.a, since the lower arm does not generate power, the output has only half of the nominal power. This effect can be appreciated in the output current (Fig.5.d) and the current arm, where the upper arm has an amplitude of 0.57 pu while the lower current is zero. The d component of the circulating current reference depends on the power difference between the arms. Therefore, when there is no power, the circulating current is zero, however, when one arm of the converter generates power, the d component of the circulating current increase to support the power unbalance. The dynamic of this current is shown in Fig.5.c, as it can be seen in the plot, the q component remains in zero because there is no power unbalance between modules of one arm. The power variation also affects the DC voltage, in the upper arm all modules increase their voltage and after 0.05s return to their reference. On the other hand the modules of the lower arm do not present any variation in the DC voltage. These results are shown in Fig.5.e and Fig.5.f respectively.

In the second test, the first 0.05s both arms operate at nominal power, therefore, the power injected into the grid is 1 pu (Fig.6.a), the current arms have the same amplitude (Fig.6.b) and the circulating current is zero (Fig.6.c). At 0.25s, the first module of the lower arm reduce its power to zero, this change decrease the output power (Fig.6.a) and a current unbalance between the arms come out (Fig.6.b). The d and the q components of the circulating current increase in order to compensate the power unbalance and thus, control the DC voltage of the module which decrease its power. At 0.45s the second module of the upper arm reduces its power from the nominal value to its 50%. This effect once again causes a power reduction in the output power and a current variation in the arms. Regarding to the circulating current, the d component is reduced since the power difference between the arms is less. However, the q component remain unchanged since the first power change at 0.25s was higher than the second power change at 0.45s.

The modulation index and the output power of all module are presented in Fig.7. The result shows that modules of each arm have the same modulation index while there is not power changes. However, when the first module of the lower arm decrease the power, its modulation index is adjusted by the local control to compensate the power change (Fig.7.a). The control increase the amplitude and a lag in the modulation index is introduced to adjust the DC voltage. In case of the second module of the upper arm, there is a similar scenario regarding to the first module of the lower arm. The modulation index is adjusted to control the DC voltage according to the voltage reference and the power change.

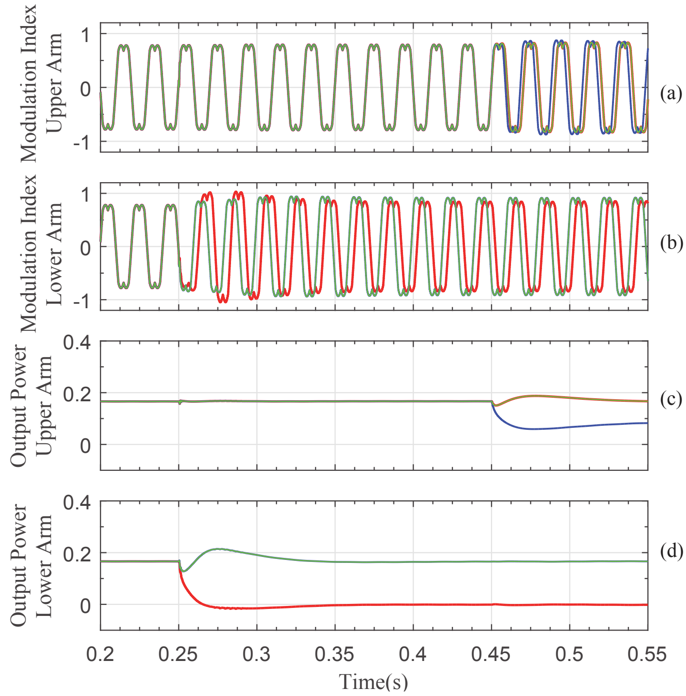

Fig. 7. Modulation index of all modules and their power variation regarding the second test. (a) Modulation index in modules of the upper arm, (b) Modulation index in modules of the lower arm, (c) Output power in modules of the upper arm, (d) Output power in modules of the lower arm.

VI. Conclusions

A new converter for medium and high voltage applications is presented in this paper. The IMMC is a multi-modular converter composed of two arms with several modules isolated connected in series. The transformer included in each module avoid the appearance of high floating voltage in the modules with respect the neutral point. For this reason, it is possible to use the converter in applications such as: photovoltaic systems and battery energy stored connected to high voltage levels without an extra DC-DC stage to provide isolation. This paper also develops a mathematical model and implements a general control strategy to operate the IMMC in different power conditions. The studies are validated using different simulation scenarios, and the analysis demonstrates that the IMMC fulfills the requirements to operate in high voltage levels with isolated modules with just one conversion stage. Furthermore, the ability to connect several modules in series proves that the IMMC is a promising configuration for high voltage AC systems.

Acknowledgment

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