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REVIEW OF CIRCULATING CURRENT CONTROL METHODS IN MODULAR MULTILEVEL CONVERTER

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ABSTRACT

An equally challenging issue with modular multilevel converter (MMC) is the circulating current which usually flows through the arms of the converter and distorts the arms currents by introducing second order harmonics, add extra losses to the converter and impacts its components ratings and amplitude of the capacitor voltage ripples. It is as a result of the variation in the instantaneous voltages among the three phases of the converter that arise from the voltage variation in the DC capacitor voltages. Circulating current needs to be properly controlled in order to improve the performance of the converter. This paper reviewed the methods of controlling the AC part of the circulating current which is responsible for the double-line frequency component in the arm currents of MMC. A mathematical model of the converter was developed where it was established that the arm current consist of three components; a fundamental component which is half of the output AC current, a DC component that is responsible for active power exchange, and a second order harmonic component. The last two components constitute the circulating current. Further analysis was conducted on one phase leg due to symmetry. In particular, common and differential modes of one phase leg of the MMC circuit were considered and analyzed independently. For the case of the differential mode, it was established that the differential voltage can be used as a control tool to control the circulating current.

Keywords: Modular multilevel converter (MMC); circulating current; circulating current control (CCC); Differential voltage; submodule (SM).

1. INTRODUCTION

Modular multilevel converter (MMC) is a member of voltage source converters (VSCs) implemented with bidirectional power flow in both single and three phase system. MMC can act as inverter - in which case, it provides energy from DC to AC side. It can also acts as rectifier where energy is provided from AC to DC side. However, unlike other VSC topologies, can provide many voltage levels at its AC side with reduced harmonic content. As one of the most innovative and highly efficient solution for energy conversion, MMC have some attractive features such as modular design, scalability to different power and voltage levels, low switching frequency, simple capacitor voltage balancing control, simple realization of redundancy, distributed location of capacitive energy storage, and nearly ideal sinusoidal-shaped output waveform (Goetz et al, 2015; Perez et al, 2015). These features makes MMC as attractive topology for applications such as high voltage direct current (HVDC) transmission system (Bergna et al., 2013; Saad et al., 2013), medium voltage motor drives (Antonopoulos et al., 2014; Hagiwara, Nishimura, & Akagi,

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2010), flexible alternating current transmission system (FACTS) (Knaak, 2011; Pirouz & Bina, 2010), and in distributed energy resources such as solar (Mei et al, 2013), and wind (Debnath & Saeedifard, 2013; Popova, et al, 2014). The converter uses components such as IGBT to achieve scalability to different voltage and power levels (Harnefors et al, 2013).

and can be controlled using different approaches. The aim of this control loop is to minimise the AC component of the circulating current which is responsible for the second order harmonics components in the arm currents with additional losses to the converter and impacts its components ratings and amplitude of the capacitor voltage ripples. *Capacitor voltage balancing (CVB)* is also a major requirement in order

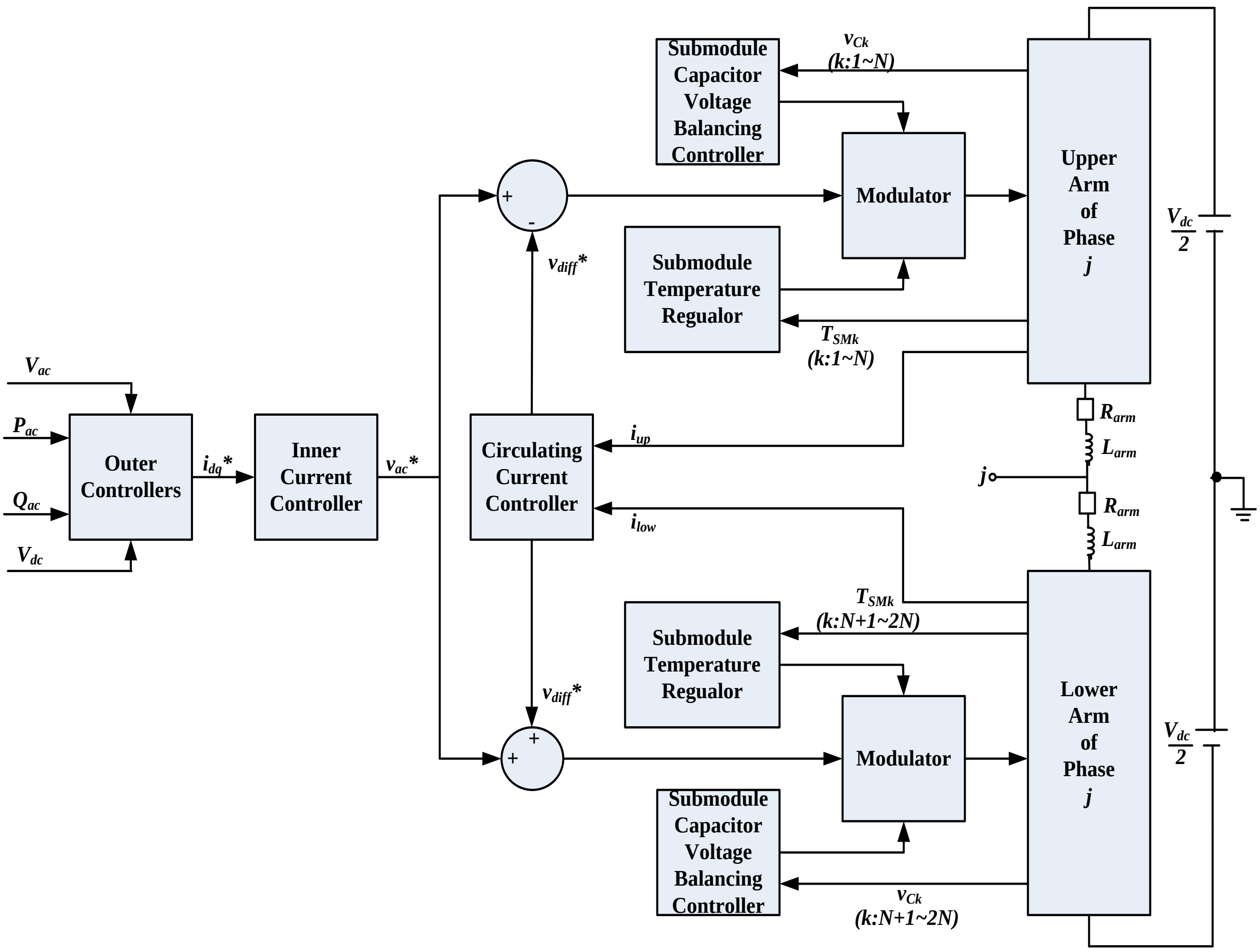

Figure 1: Block diagram of MMC Control loops

Many parameters need be controlled in order to achieve proper operation of MMC, regardless whether it is used as inverter or rectifier. As such cascaded and chained control loops are required for proper operation of the converter. The block diagram in figure 1 shows an exemplary approach to MMC control strategy. *The Circulating Current Control (CCC)* is a major requirement for proper operation of MMC

to achieve equal power distribution among the SMs. Several methods have been proposed to address capacitor voltage balancing with the common ones being distributed and centralized methods (Fan et al, 2015). The *distributed method* employs carrier phase-shifted pulse-width modulation (CPS-PWM) in a closed-loop control to balance the capacitor voltage to its reference value (Hagiwara, Maeda, &

Akagi, 2011; Li et al, 2016). However, the balancing is achieved with some modification on the modulating signal but can provide good balancing at high switching frequency. The *centralized method* takes into account the capacitor voltages and arm current polarities to select certain SMs for certain switching states (Dekka et al, 2016; Wang, Li, Zheng, & Xu, 2013). The centralized methods are normally applied with sorting algorithm. As such, fast sorting of capacitor voltages in a complex system with large number of SMs will be an issue (Siemaszko, 2015). *The submodule temperature regulation (SMTR)* may only be necessary if thermal analysis is required so that the thermal stress within the converter SMs will be regulated. This control loop is typically linked to the individual SM capacitor voltage control loop where the control algorithm is modified to include SM temperature into account (Gonçalves, Rogers, & Liang, 2018). In this way, an indirect active thermal control is achieved.

Circulating current is an inherent feature of MMC. It is as a result of the variation in the instantaneous voltages among the three phases of the converter that arise from the voltage variation in the DC capacitor voltages. The effect of uncontrolled circulating current translates into second order harmonics on the arm current, increased current loading and loss distribution on the semiconductor devices of the converter. In the design stage, arm inductors are used to suppress the second order harmonic component of circulating current which is the component responsible for second order harmonic in arm currents of the converter. However, increasing the size of the arm inductor increases the size, weight and cost of the converter. This call for a tailored control algorithm for suppressing the circulating current. Several CCC methods have been proposed in the literature for one purpose or the other. However, there was no attempt to put all the proposed control methods into one article. This paper reviewed different methods for the control of AC component of circulating current in MMC with a view of pointing out how best to choose a control method for a particular application. The remaining part of this paper is organised as follows. Section 2 presents circuit schematic and operating principle of MMC. In section 3, the concept of circulating current in MMC is presented. Section 4 presents a review of CCC in MMC. Finally, conclusions are stated in Section 5.

2. CIRCUIT SCHEMATIC OF MODULAR MULTILEVEL CONVERTER

The circuit schematic of three phase MMC is shown in figure 2. A phase is made up of two identical arms; upper and lower that are connected in series through arm inductors. An arm is made up of identical series connected chopper cells known as *submodules* (SMs) and an arm inductor. An SM can be configured in one of the following (Konstantinou, Zhang, Ceballos, Pou, & Agelidis, 2015); half bridge SM (HB-SM), full bridge SM (FB-SM), flying capacitor SM (FC-SM), diode clamped SM (DC-SM), T-Submodule 1 (TSM1) or T-Submodule 2 (TSM2). HB-SM is more common because of its simplicity in terms of component count, lowest losses and easy control method. Each of the HBSM consists of two controlled semiconductor switches (IGBTs in this case) with associated anti-parallel diodes, and a DC capacitor for energy storage. The arm inductance is used to limit the amplitude of the circulating current through the arm and possible fault current. It also allows small mismatch in the arm voltages. V_{dc} is the input DC voltage, L_{arm} and R_{arm}, are the arm inductance and its resistance, i_{up} and i_{low} are the currents through the upper and lower arm respectively, v_{up} and v_{low} are the respective arm voltages, i_{circ} is the circulating current that flows within the arms of the converter without appearing at its output, L_{load} and R_{load} represents an RL load, i_{ac} and v_{ac} are the output AC current and voltage respectively, i_{SM} and v_{SM} are SM current and voltage respectively, C is the SM capacitor and v_C is the SM capacitor voltage, T_{up} and D_{up} are the upper IGBT and diode in the SM while T_{low} and D_{low} are the lower IGBT and diode in the SM.

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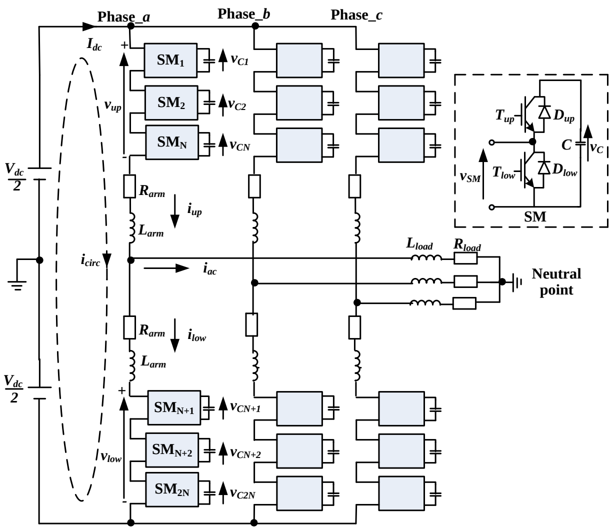

Figure 2: Circuit Schematic of Three-phase MMC

3. CIRCULATING CURRENT IN MODULAR MULTILEVEL CONVERTER

Owing to the symmetry nature, the analysis of circulating current in MMC can be carried out on one phase.

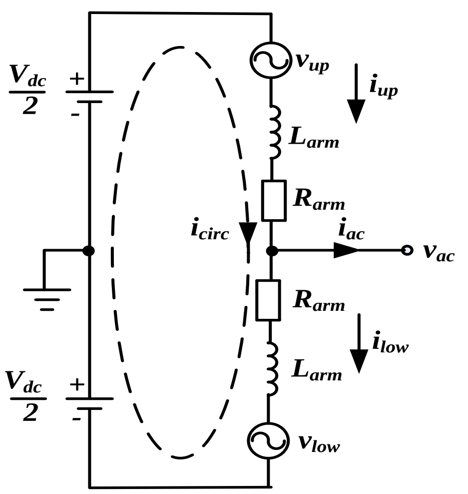

Figure 3: Equivalent circuit of one phase of MMC

Figure 3 shows the equivalent circuit of one phase of MMC in which the SMs in both arms are treated as multilevel voltage sources. The circulating current, i_{circ}, and the output AC current i_{ac} can be expressed as:

$$i_{circ} = \frac{i_{up} + i_{low}}{2} \tag{1}$$

$$i_{ac} = i_{up} - i_{low} \tag{2}$$

From (1) and (2), the arm currents can be expressed as:

$$i_{up} = \frac{i_{ac}}{2} + i_{circ} \tag{3}$$

$$i_{low} = \frac{i_{ac}}{2} - i_{circ} \tag{4}$$

Application of Kirchhoff voltage law (KVL) gives the arm voltages as:

$$v_{up} = \frac{V_{dc}}{2} - v_{ac} - L_{arm}\frac{d}{dt}i_{up} - R_{arm}i_{up} \tag{5}$$

$$v_{low} = \frac{V_{dc}}{2} + v_{ac} - L_{arm}\frac{d}{dt}i_{low} - R_{arm}i_{low} \tag{6}$$

Combining (2) with (5) and (6), the AC output dynamics of the converter can be expressed as:

$$v_{ac} = \frac{1}{2}(v_{low} - v_{up}) - \frac{L_{arm}}{2}\frac{d}{dt}(i_{up} - i_{low}) \tag{7}$$

Combining (1) with (5) and (6), the inner dynamics of the converter can be expressed as:

$$L_{arm}\frac{d}{dt}i_{circ} + R_{arm}i_{circ} = \frac{V_{dc}}{2} - \frac{(v_{up} + v_{low})}{2} \tag{8}$$

Fom (7) and (8), two important terms, namely the inner e.m.f generated in the phase, e_j, and the difference voltage, v_{diff} can respectively be obtained as:

$$e_j = \frac{v_{low} - v_{up}}{2} \tag{9}$$

$$v_{diff} = L_{arm}\frac{d}{dt}i_{circ} + R_{arm}i_{circ} \quad (10)$$

Substituting (9) and (10) into (5) and (6) gives the arm voltage reference as:

$$v_{up}^{*} = \frac{V_{dc}}{2} - e_j - v_{diff} \quad (11)$$

$$v_{low}^{*} = \frac{V_{dc}}{2} + e_j - v_{diff} \quad (12)$$

Considering one phase leg of the MMC, two independent circuits; common and differential modes can be obtained as shown in fig. 4. The two circuits can be analyzed separately. Application of superposition theorem gives the common voltage v_{comm}, common current i_{comm}, differential voltage v_{diff}, and differential current i_{diff} as:

$$v_{comm} = \frac{v_{up} + v_{low}}{2} \quad (13)$$

$$i_{comm} = \frac{i_{ac}}{2} \quad (14)$$

$$v_{diff} = \frac{v_{up} - v_{low}}{2} \quad (15)$$

$$i_{diff} = \frac{1}{L_{arm}}\int_{t_0}^{t_1} v_{diff}dt + I_{diff0} = i_{circ} \quad (16)$$

where I_{diff0} is the initial value of the differential current. The above equations show, the differential voltage can be used to control the differential current.

The differential current, i_{diff} circulates through the arms of the converter without appearing on the output AC current and is therefore called the circulating current, i_{circ}. Based on the foregoing, the arm currents can be expressed as:

$$i_{up} = i_{comm} + i_{diff} = \frac{i_{ac}}{2} + i_{circ} \quad (17)$$

$$i_{dn} = i_{comm} - i_{diff} = \frac{i_{ac}}{2} - i_{circ} \quad (18)$$

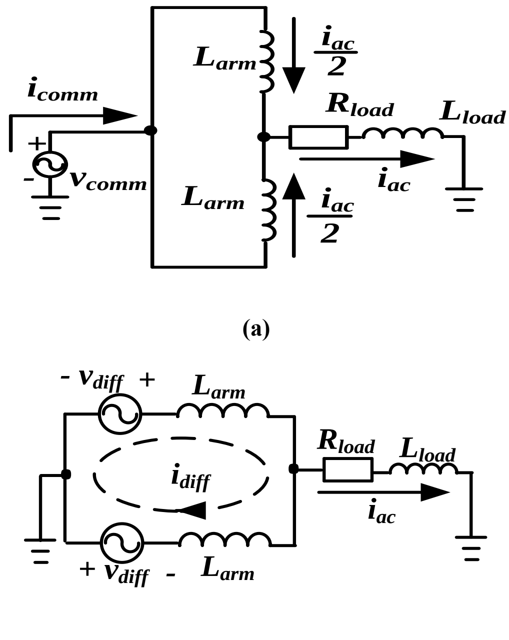

Figure 4: Common and differential mode of MMC leg (a) Common mode, (b) Differential mode

Equations (17) and (18) show that the arm currents consist of three components; a fundamental component which is half of the output AC current, a DC component that is responsible for active power exchange, and a second order harmonic component. The last two components constitute the circulating current. Based on the foregoing, the three phase circulating currents can be expressed as:

$$i_{circ\_a} = \frac{I_{dc}}{3} + i_{2f}\sin(2\omega_o t + \varphi_o) \quad (19)$$

$$i_{circ\_b} = \frac{I_{dc}}{3} + i_{2f}\sin(2\omega_o t + \frac{2\pi}{3} + \varphi_o) \quad (20)$$

$$i_{circ\_c} = \frac{I_{dc}}{3} + i_{2f}\sin(2\omega_o t - \frac{2\pi}{3} + \varphi_o) \quad (21)$$

where I_{dc} is the total DC current, i_{2f} is the peak value of the double line-frequency circulating current, ω_o is the fundamental frequency and φ_o is the initial phase angle.

4. METHODS OF CIRCULATING CURRENT CONTROL (CCC)

4.1. CCC Based on Double Line-Frequency *dq* Coordinate

One approach for circulating current control is based on the negative-sequence double line-frequency *dq* transformation (Tu, Xu, & Xu, 2011) in which the three phase time varying circulating current are transformed into two DC components. Re-writing (10) in *a-c-b* phase sequence gives:

$$\begin{bmatrix} v_{diff\_a} \\ v_{diff\_c} \\ v_{diff\_b} \end{bmatrix} = L_{arm}\frac{d}{dt}\begin{bmatrix} i_{circ\_a} \\ i_{circ\_c} \\ i_{circ\_b} \end{bmatrix} + R_{arm}\begin{bmatrix} i_{circ\_a} \\ i_{circ\_c} \\ i_{circ\_b} \end{bmatrix} \qquad (22)$$

The *abc-dq* transformation matrix is given as:

$$T_{abc/dq} = \frac{2}{3}\begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \qquad (23)$$

where $\theta = 2\omega_o t$

Substituting (19), (20) and (21) into (22) and multiplying with (23) gives:

$$\begin{bmatrix} v_{diff_d} \\ v_{diff_q} \end{bmatrix} = L_{arm}\frac{d}{dt}\begin{bmatrix} i_{2f_d} \\ i_{2f_q} \end{bmatrix} + \begin{bmatrix} R_{arm} & -2\omega L_{arm} + R_{arm} \\ 2\omega L_{arm} + R_{arm} & R_{arm} \end{bmatrix}\begin{bmatrix} i_{2f_d} \\ i_{2f_q} \end{bmatrix} \qquad (24)$$

where v_{diff_d} and v_{diff_q} are the *d* and *q* components of the differential voltage, i_{2f_d} and i_{2f_q} are the *d* and *q* components of the circulating current.

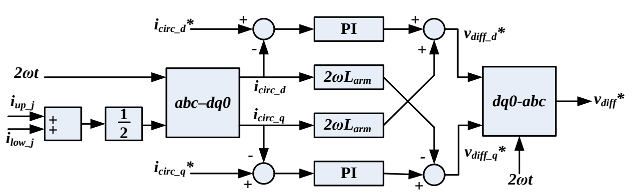

Figure 5: CCC based on double line frequency *dq* transformation *(Tu, Xu, & Xu, 2011)*

The control strategy is shown in figure 5. It can be seen in (24) that the differential voltage can be used to control the circulating current. The reference values of the circulating current, $i^*_{2f\_d}$ and $i^*_{2f\_q}$ were set to zero and two PI controllers with cross coupling compensation were used to obtain the control signals $v^*_{diff\_d}$ and $v^*_{diff\_q}$ for minimising the AC component of the circulating currents. The *dq* transformation is capable of mapping the fundamental frequency components of the AC circulating current into DC values allowing easier design of controller.

4.2. CCC Based on Instantaneous Power

Another CCC method is based on the instantaneous information of the converter (Pou et al., 2015) where the instantaneous values of the output current and modulation signal were used to set the references values for the circulating current. This approach involves detailed analysis of the converter, evaluating total energy stored in the arms and setting three different references for the circulating current, namely; a DC component only, a DC component with second harmonic term, and based on the instantaneous value of the output current of the phase leg.

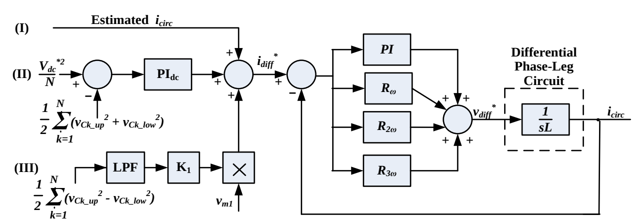

Figure 6: CCC based on instantaneous power *(Pou et al., 2015)*

The control scheme is shown in figure 6 and it consists of three parts. The first part is the estimation of the instantaneous reference value of the circulating current. The differential current reference is determined from the instantaneous information of the converter in which the SMs of one arm are set to the same duty cycle forcing their capacitors to charge and or discharge in the same passion. In this way, the average value of the SMs capacitance will be larger than the value of individual SM capacitances. The estimated value of the differential current contains DC current component which is required to balance the power in the phase leg, as such an additional controller is required for the DC current. The second part involves generating additional DC current that is needed to regulate the average energy stored in the SM capacitors to

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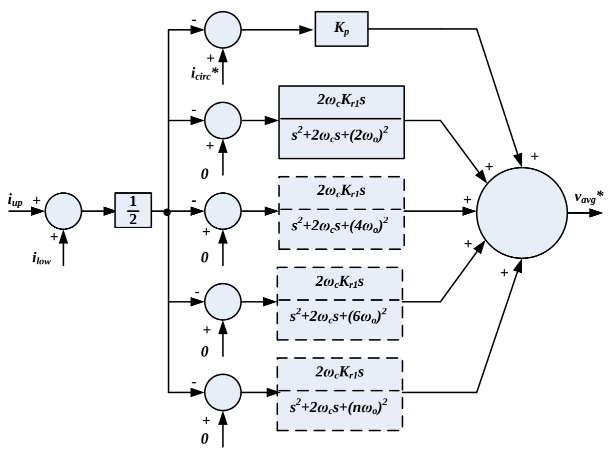
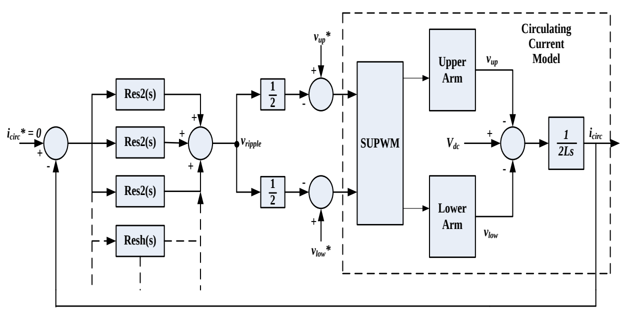
their reference value and a conventional PI controller is used for this purpose. The third part involves fundamental frequency current component that is required for the exchange of energy between the converter arms and also for balancing their energy. It can be noted that this particular part of the control structure is synchronised with the fundamental component of the modulation signal for optimal performance.

4.3. CCC Based on PR Controllers

In this technique, an additional minor control loop consisting of multi-frequency proportional resonant (PR) controllers is added to the MMC control based on CPS-PWM to regulate the AC part of circulating current with multi-frequency components to zero and the DC component to a desired value (She et al, 2012). Based on the system parameters, different resonant frequencies were selected, and the control loop was able to suppress not only the double line frequency components of the AC circulating current, but also even harmonic components. The block diagram of this control strategy is shown in figure 7(a).



(a)



(b)

Figure 7: CCC based on PR controllers

(a) Based on CPS-PWM *(She et al, 2012)*, **(b) Based on SU-PWM** (*Li et al (2013)*

Li et al (2013) proposed another CCC control based on PR controllers with different modulation technique. In this case, a closed loop PR controller is implemented in stationary frame and submodule unified pulse width modulation (SU-PWM) technique is used. The circulating current is determined by the ripple component of the arm voltages as can be seen in figure 7(b).

4.4. CCC Based on Level Redundancies

In this technique, the circulating current is regulated to its reference value by the available redundancies in the MMC controlled with *2N+1* modulation (Konstantinou et al., 2016). The method is peculiar to technique that gives *2N+1* voltage levels at the output which is typically implemented by phase shifting the upper and lower arm carrier signals by 180° or by direct modulation of *2N+1* level). The controller is implemented in the modulation stage and is independent of the circulating current reference. The circulating current is measured and compared with the reference value. *N+1* SMs will be connected to the phase leg if the measured value is greater than the reference. On the contrary, *N-1* SMs will be connected to the phase leg if the measured value is lower than the reference value. In this way, a transition is established from non-redundant (NR) state to redundant (R) state as shown in fig. 8(a). The controller is very simple to implement as shown in fig. 8(b) and has very fast dynamic.

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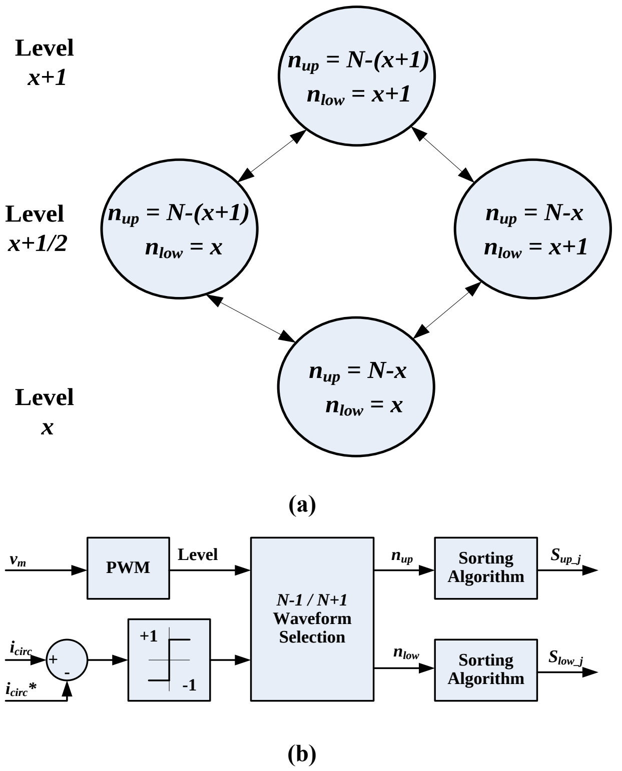

Figure 8: CCC based on level redundancies *(Konstantinou et al., 2016).*

(a) Transition between adjacent levels and number of activated SM in 2N+1 modulation, (b) Control method

4.5. CCC Based on Moving Average Filters

Darus et al (2013) proposed another approach for eliminating circulating current and minimising losses in MMC. Two methods were used to control the circulating current and reduce the amplitude of capacitor voltage ripple. In the first method, AC and DC components of the circulating current were separated, where the AC component was forced to zero with the aid of high pass filter based on moving average filter (MAF). As can be seen in figure 9, the differential voltage, v_{diff} is used to control the AC component of the circulating current while an external controller is used to adjust the DC component of the circulating current which is allowed to circulate within the converter. In the second method, the reference values for the AC and DC components of the circulating current were obtained separately. The reference for the AC component was obtained from the measurement and control of SM capacitor voltages while that of the DC component was obtained from the calculation of DC side current. These parameters and the measured values of the arm currents were used to calculate the circulating current.

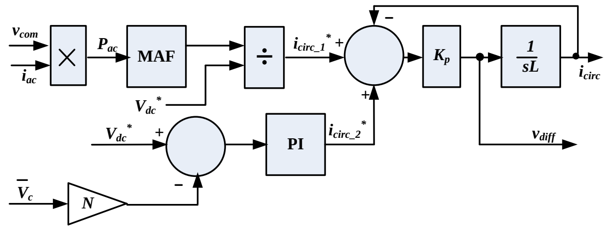

Figure 9: CCC based on moving average filter (*Darus et al, 2013)*

4.6. CCC Based on Repetitive Controllers

This approach involves combining high dynamics of the conventional PI controller with the good harmonic suppression capability of repetitive controller to eliminate the multiple harmonics in the circulating current (He, et al 2015). As can be seen in figure 10, the two controllers connected in parallel were designed independently such that the repetitive controller focuses on the error left by the PI controller.

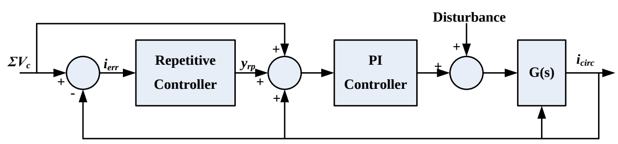

Figure 10: CCC based on repetitive control scheme *(He, et al 2015)*

4.7. CCC Based on Predictive Control

Model predictive control (MPC) as another means of suppressing circulating current in MMC while maintaining the SM capacitor voltages to their reference values (Qin & Saeedifard, 2012). The concept employs a discrete mathematical model of the converter in defining cost function for the converter control and circulating current suppression. It also involves evaluation and minimisation of a defined cost function related to the converter control and using it to select the appropriate switching state of each unit of the system that will result in minimum value for the defined cost function. For a sampling time of T_s, the discrete model of circulating current can be expressed as (Qin & Saeedifard, 2012):

$$i_{circ}(t+T_s) = \frac{T_s}{2L_{arm}}\Big(V_{dc} - v_{up}(t+T_s) - v_{low}(t+T_s)\Big) + i_{circ}(t) \tag{25}$$

The initial cost function, J_{j_g} can now be modified to J'_{j_g} by including an additional term for capacitor voltage deviation.

$$J'_{j\_g} = J_{j\_g} + ɰ_{C\_g}\left(\sum_i \left|v_{C\_kjg}(t+T_s) - \frac{V_{dc}}{N}\right|\right) \tag{26}$$

where $ɰ_{C\_g}$ is a weighing factor evaluated empirically and is tuned based on the cost contributions assigned to the capacitor voltages deviations, and $v_{C\_kjg}(t+T_s)$ is the next predicted capacitor voltage of SM k, of phase j of arm g. In order to achieve desired performance in the elimination of the circulating current for which the MPC algorithm is aimed at, a circulating current term is added to the cost function. As such, (26) can be re-written as:

$$J''_{j\_g} = J_{j\_g} + \lambda_{C\_g}\left(\sum_i \left|v_{C\_kjg}(t+T_s) - \frac{V_{dc}}{N}\right|\right) + ɰ_{circ\_g}\left|i_{circ\_jg}(t+T_s)\right| \tag{27}$$

4.8. CCC Based on Energy Measurement

Another method of eliminating the circulating current between the phase legs of MMC is by a controller that balances the total energy and that in the upper and lower arm of the converter regardless of the imposed alternating current (Antonopoulos, Angquist, & Nee, 2009). The method assumed a continuous model where all the SMs in the upper and lower arm of the converter are treated as variable voltage sources disregarding the pulse width modulation (PWM) effect. The approach is based on measuring the SM voltages and computing the sum and difference of the total energy of the converter arms.

Two controllers are used to achieve the balancing. In particular, a PI controller is used to balance the total energy within the converter and a P controller which suppress the AC component of the circulating current.

The sum of the energy in upper arm, W_{up}^{Σ} and that of the lower arm, W_{low}^{Σ} gives total energy, W_j^{Σ} in phase j of the converter.

$$W_j^{\Sigma} = W_{up}^{\Sigma} + W_{low}^{\Sigma} \tag{28}$$

Accordingly, the energy difference between the two arms can be expressed as:

$$W_j^{\Delta} = W_{up}^{\Sigma} - W_{low}^{\Sigma} \tag{29}$$

The derivatives of the stored energy in the converter arms can be expressed as:

$$\frac{d}{dt}W_{up}^{\Sigma} = \left(\frac{i_{ac}}{2} + i_{circ}\right)\left(\frac{V_{dc}}{2} - e_j - v_{diff}\right) = i_{up}v_{up} \tag{30}$$

$$\frac{d}{dt}W_{low}^{\Sigma} = \left(\frac{i_{ac}}{2} + i_{circ}\right)\left(\frac{V_{dc}}{2} + e_j - v_{diff}\right) = i_{low}v_{low} \tag{31}$$

The derivatives of total energy of the two arms and that of their difference can now be expressed as:

$$\frac{d}{dt}W_j^{\Sigma} = (V_{dc} - 2v_{diff})\ i_{circ} - e_j i_{ac} \tag{32}$$

$$\frac{d}{dt}W_j^{\Delta} = -2e_j i_{circ} + \left(\frac{V_{dc}}{2} - v_{diff}\right) i_{ac} \tag{33}$$

The above equations show the dependency of total energy of the converter on the circulating current. The DC component of the circulating current in (32) balances the power transferred to the AC s1ide and compensate for the losses caused by the differential current on the arm inductor and resistor. In (33) however, there are no DC components in e_j or i_{ac_j}, hence, the DC component of the circulating current has no impact on the derivative of the energy difference between the two arms. As such, the energy stored in the SM capacitors can be controlled by the circulating current in each leg. On the contrary, the fundamental component of the circulating current will affect the energy distributed between the SM capacitors in upper arm and that of lower arm. Based on this, two cascaded control loops are required; one to balance the total energy in the converter and the other to balance the energy between the two arms of the converter. The block diagram of this control strategy is shown in figure 11.

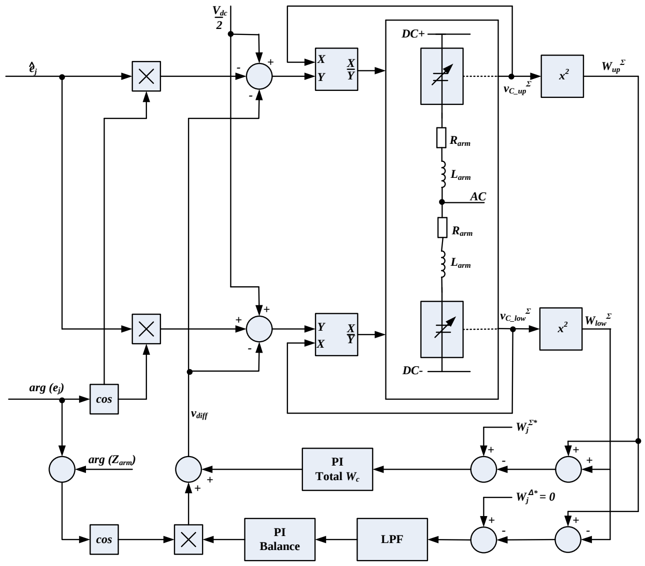

Figure 11: CCC based on energy measurement *(Antonopoulos, Angquist, & Nee, 2009).*

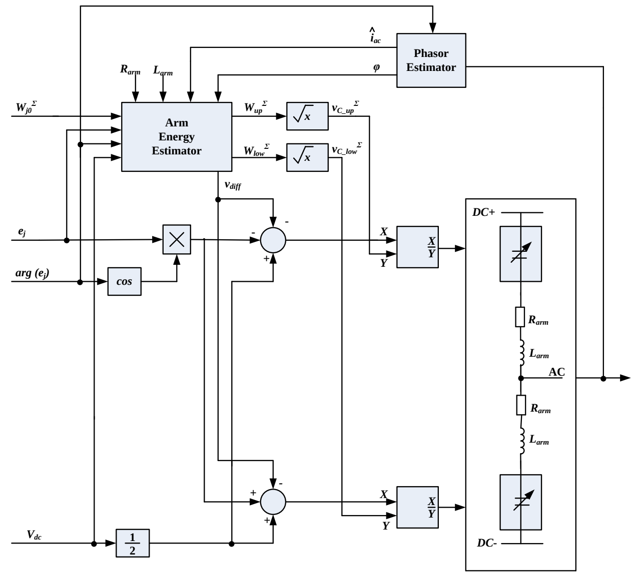

Figure 12: CCC based on energy estimation *(Ängquist et al., 2010).*

4.9. CCC Based on Energy Estimation

The method based on energy balancing requires consistent measurement of all SM voltages. As such it may be costly or less reliable to use in converters with large number of SMs such as the ones used in HVDC systems as it involves many sensors. The method based on energy estimation is a simplification of the one based on energy balancing. In this case, the arm energy is estimated from the measured AC output current and DC voltage (Ängquist et al., 2010). Open loop controllers are then designed to balance the total energy in the converter arms and to suppress the AC component of the circulating current. Figure 12 shows the block diagram of this control strategy.

4.10. Other CCC Methods

Li, Jones & Wang (2017) proposed a theoretical relationship switching frequency circulating current and the arm inductance that is used to limit the AC part of circulating current. Simulation and experimentally validated results show that arm inductor selection is limited by the switching frequency circulating current. Hassani, Bektas, & Hosseini, (2017) proposed another CCC based on model predictive control with genetic algorithm. The algorithm generates the optimum insertion indices for the upper and lower arm of the converter for providing appropriate gating signals (switching pulses). However, this method is based on submodule sorting algorithms, as such, is not applicable when distributed method of capacitor voltage balancing is employed, Chen, et al (2017) proposed a modified CCC for nearest level control based MMC. The method was based on hysteresis control where peak to peak value of the circulating current is approximately limited within the peak band. The proposed method has very fast dynamic performance but difficult in terms of controller tuning.

Oliveira & Yazdani, (2018) investigates an enhanced damping control for suppressing the AC component of circulating current in MMC using feedforward control strategy. The amplitude of the second order harmonic component of the arm voltage are calculated offline and uses same in feedforward manner to cancel the double line frequency component of the circulating current. The method is easy to implement without any auxiliary control algorithm. However, there is no feedback in the control. Pérez-Basante, et al (2018) formulated CCC algorithm based on (2N+1) selective harmonic elimination pulse width modulation (SHE-PWM) for medium voltage MMC. The algorithm was able to minimise the circulating current and reduces the losses in the converter significantly. However, SHE technique allows the cancellation of any unwanted harmonics and also allows the control of the amplitude of the fundamental frequency component. However, since the switching angles are calculated offline, the technique is limited to open loop system. Furthermore, SHE technique is not applicable to converters with high number of levels due to many switching angles that need to be calculated.

Zhang, et al (2019) investigate a CCC for an MMC supplying passive network under unbalanced load conditions. The method is based on instantaneous information of the converter with overcurrent consideration. In this method, controller tuning is easy. However, the overcurrent limitation offers a compromise between peak arm currents and capacitor voltage ripples

Chen, et al (2020) proposed another CCC method based on deadbeat control with increased nearest level modulation (NLM). The method is based on adjusting the total number of inserted SMs to suppress circulating current and improve the dynamic control performance. The method is only restricted to NLM technique which is not based on carrier signals. Chakraborty R. & Dey, A (2020) proposed another CCC method with reduced conduction losses for voltage applications. The control method incorporates arm inductor voltages in modelling the circulating current by defining a new reference value. However, for high voltage applications such as HVDC for which MMCs are intended for, including the arm voltage the CCC (which is very small compared to the system voltage) will not make a difference, instead will increase the cost of the system because more sensors will be required. Tanta et al, (2020) proposed deadbeat predictive current control to suppress the AC component of circulating current in an MMC for railway system application. The method improves power quality of the system but the modulation strategy has unmodeled delays with many modelling assumptions. Perez-Basante *et al (2020*) proposed another CCC for MMC with (N+1) SHE-PWM. The method is based regulating the energy stored in the SM to their given references while maintaining the energy balance both arms of each phase of the converter. The method improves efficiency of the converter significantly. However, it requires larger SM capacitors to limit some inherent voltage oscillations associated with the control strategy.

4.11. Summary and Recommendation

In summary, it can be seen from the literature that the current CCC methods are based on modifying the reference modulation signals of the converters arms through different modulation techniques. The modulation techniques can be summarized into two basic categories; space vector based algorithms and voltage level based algorithms. The techniques under space vector modulation (SVM) are based on alpha-beta plane and when the zero sequence component is required to be controlled, a gamma axis is added to the plane as with the case of 2 dimensional SVM and 3 dimensional SVM respectively. However, SVM techniques are not suitable for MMC with large number of SMs because the number of space vectors increases proportionally to the cubic of the number of voltage levels. On the contrary, the voltage level based algorithms can easily be implemented in MMC with large number of SMs independent of the switching frequency. For high frequency modulation, phase-shifted PWM and level-shifted PWM are preferred choice while for low frequency modulation, selective harmonic elimination and nearest level modulation will be the preferred choice. However, for MMC with large number of SMs such as in the case of HVDC system, selective harmonic elimination technique will be impractical since many switching angles has to be calculated giving room for nearest level modulation as an alternative.

The mathematical model of the MMC reveals that circulating current is an inherent feature of the converter. As such, it is worth considering alternative means of CCC right from the design stage of the converter. Although arm inductors are used to limit the circulating current, but they cannot be over-sized to some extent. In this regard, active (electronic) filters can be considered. Another recommendation is the use of sensorless controllers that will modify the duty cycles of the semiconductors.

5. CONCLUSION

Circulating current control is a major requirement for proper operation of MMC. In this paper, different methods for the control of circulating were reviewed. Some of the methods uses sensors to balance the energy between the converter arms while other methods works based on estimation. In terms of controller types, some methods uses PI controllers while others uses PR controllers. On the contrary, some methods are based on the instantaneous information of the converter while others are based on negative-sequence double line-frequency *dq* transformation. The choice of the circulating current control may be related to the modulation technique, cost of hardware/software and efficiency. For example, the method base on arm energy measurement and control will be more efficient than the method based on energy estimation on one hand but will cost much in terms of cost of hardware and software in a system with large number of SMs.

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