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Simple Topologies for AC-Link Flexible AC Transmission Systems

Julio C. Rosas-Caro, Juan M. Ramirez, Fang Z. Peng

***Abstract*--Vector Switching Converter VeSC has been recently introduced as an alternative for controlling power flow in power system's complex interconnections by direct AC-AC conversion, and novel FACTS devices have been recently introduced based on the VeSC, such as the *Xi* (Ξ) and *Gamma* (Γ) controllers.**

This paper introduces the Simplified Vector Switching Converter SVeSC and the topology of the *Xi* (Ξ) and *Gamma* (Γ) controllers based on this novel simplified scheme, which reduce the number of switches, increasing the reliability and reducing the cost of implementation, while holds the operating principle. The control system of AC-link FACTS devices is simpler than the control system of the DC-link approach, and free of PLL and trigonometric calculations.

Simulation results of the active power flow control between two nodes by the proposed simplified *Xi* (Ξ) controller are provided to prove the operating principle.

***Index Terms* – FACTS, series compensator, power flow control, ac-ac converter.**

I. Introduction

Flexible Alternating Current Transmission Systems (FACTS) controllers improve the transmission system operation [1], achieving highly desirable capabilities. Due to the increment of power demand and economical issues on the deregulated scenario [2], several devices such as the Static Synchronous Compensator *STATCOM*, the Static Synchronous Series Compensator *SSSC,* and the Unified Power Flow Controller *UPFC* have been introduced [1-2]; they are based on DC-AC converters.

On the other hand, AC-AC direct converters (with frequency change capability or not) have been proposed and analyzed for utility applications such as custom power and power flow control [2-25]. AC-AC converters with no frequency change capability are simpler and cheaper than the matrix converter. They are derived from the DC-DC converters and are able to modify the AC voltage amplitude; such converters will be called *AC-link converters*.

Transformers in AC-link converters give the possibility to shift the AC signal by them and modify the amplitude by PWM [4-8]. Vector Switching Converters VeSC have been recently proposed for power flow controlling in complex interconnections [2], and several FACTS controllers and power conditioners has been developed using AC-link converters and transformer assisted AC-link converters such as the Ξ and Γ controllers [2-19]. Utilizing the Ξ controller as example, it has been shown in [20] that the AC-link approach reduces the cost of FACTS devices applied for power system operation improvement [20-23].

This paper introduces the Simplified Vector Switching Converter SVeSC as a new member of the Vector Converter's family. The topology is simpler and cheaper than the VeSC and can be applied for developing FACTS controllers and Power Conditioners with a reduced number of switches.

Some advantages of the SVeSC AC-link based compensators compared to the conventional DC-link based compensators are as follows.

(i) It does not have an energy-stored element which is the most unreliable part of the DC-link voltage source converter *VSC*.

(ii) The controller does not need a PLL nor trigonometric calculations. Signals' phase is fixed and depend on the transformers' arrangement and some passive filters. Within the DC-link approach, the PLL is very important and sometimes very complex because losing the synchronous operation can destroy the converter. In the AC-link approach this never happen, the controller is insensitive to frequency variations, improving the stability.

(iii) Such controllers are cheaper than the conventional DC-link based compensators.

(iv) Power stage requires fewer switches, which improve the reliability.

It will be shown how the AC-link FACTS controllers already proposed such as the Γ and Ξ controllers can be implemented by the SVeSC. Simulation results in a SVeSC based Ξ controller for power flow control are provided to prove the operating principle.

II. Vector Switching Converter

VeSC have been proposed an analyzed in [2]; Fig. 1 shows a three-throw single-pole three-phase VeSC. This topology feeds one three-phase load by three stiff three-phase voltage sources.

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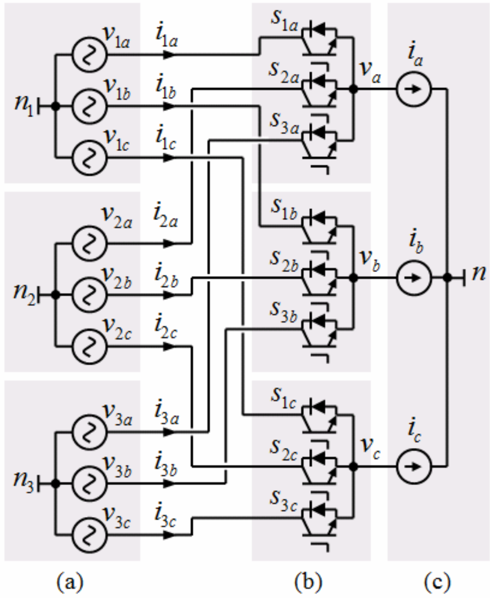

Fig. 1. Three-phase **3x1** vector switching converter

The designation of stiff voltage or current sources is arbitrary because of a stiff voltage/current source may be transformed into a stiff current/voltage source by adding a series inductor or shunt capacitors, respectively, in order to fit application considerations [2, 19]. For analysis, switches are considered ideal. Within an actual converter, filter elements are appropriately applied and snubber circuits (optional) would ensure the correct behavior [2].

Three three-phase voltages (Fig. 1(a)) are connected through three single-pole three-throw switches (Fig. 1(b)), to a three-phase load (Fig. 1(c)). Each switch is constituted by three IGBTs and three anti-parallels diodes. IGBTs S_{1a}, S_{1b} and S_{1c} open and close at the same time, and t_{1on} is the time when they are closed. Similarly, S_{2a}, S_{2b} and S_{2c} open and close at the same time, and t_{2on} is the time when they are closed, and t_{3on} is the time when S_{3a}, S_{3b} and S_{3c} are closed. T is the total switching period.

Taking such considerations into account, then three switches' duty cycles may be defined as follows,

$$d_1 = \frac{t_{1on}}{T}; \qquad d_2 = \frac{t_{2on}}{T}; \qquad d_3 = \frac{t_{3on}}{T} \tag{1}$$

Two voltage sources must never been connected in parallel or an over current can destroy the switches, and the load must never be disconnected or the load current can generate a high voltage that would destroy the converter. That is why one throw of each switch must be closed at any time, but not more than one. Mathematically this can be expressed in the duty cycles as:

$$\frac{t_{1on} + t_{2on} + t_{3on}}{T} = d_1 + d_2 + d_3 = 1 \tag{2}$$

The average load voltage can be expressed in terms of the duty cycles and the input voltages as follows.

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} v_{1a}(t) & v_{2a}(t) & v_{3a}(t) \\ v_{1b}(t) & v_{2b}(t) & v_{3b}(t) \\ v_{1c}(t) & v_{2c}(t) & v_{3c}(t) \end{bmatrix} \begin{bmatrix} d_1(t) \\ d_2(t) \\ d_3(t) \end{bmatrix} \tag{3}$$

The average current for each input voltage source can be expressed in terms of duty cycles and load current,

$$\begin{bmatrix} i_{ia}(t) \\ i_{ib}(t) \\ i_{ic}(t) \end{bmatrix} = d_i \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{4}$$

For $i = 1, 2, 3$. It is worth noting that the converter shown in Fig. 1 can be extended to any number of loads, adding three single-pole three-throw switches for each three-phase load, and to any number of input voltage sources, adding an IGBT and anti-parallel diode to each switch [2].

The structure in Fig. 1 looks like a three-phase matrix converter, the main difference in the power stage is that the matrix converter needs 18 IGBTs, while the vector converter requires 9. Voltage sources in the vector converter need to be isolated, which can be achieved with transformers; that isolation is the reason because the VeSC doesn't require bidirectional switches.

The output voltage is the sum of products of duty cycles, and the input voltage which have a vector representation. The output voltage vector may be analyzed as in Fig. 2. If the input voltages v_{1a}, v_{2a} and v_{3a} exhibit 120° phase shift, then the attainable output voltage v_a may possesses any phase. The vector can be inside the light gray triangle in Fig. 2. In order to maintain the amplitude and phase independent, the output voltage should be limited to be inside the dark gray circle in Fig. 2. To get the black voltage in Fig. 2, the duty cycles should be $d_1=0.5$, $d_2=0$ and $d_3=0.5$ ($d_1+d_2+d_3=1$).

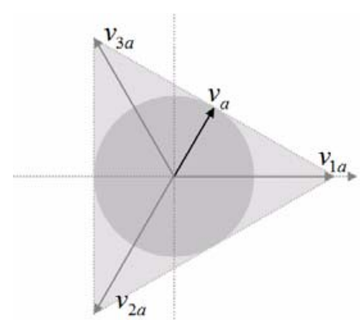

Fig. 2. Attainable output voltage for three input voltage with 120° phase shift

Fig. 3 displays additional details about the converter in Fig. 1. It represents the same configuration, the phase shift transformer get three three-phase voltage sources with 120° phase shift, they are Y-Y connected, but delta configuration can also achieve the purpose. Capacitors may be utilized to decouple the transformer's inductance. Thus, a parallel capacitor transforms a current source into a voltage one. For simulation and analysis purposes those capacitors can be neglected, but for a real application they must be considered.

The VeSC is an AC-link converter and it is used to develop FACTS controllers such as the Ξ and Γ controllers.

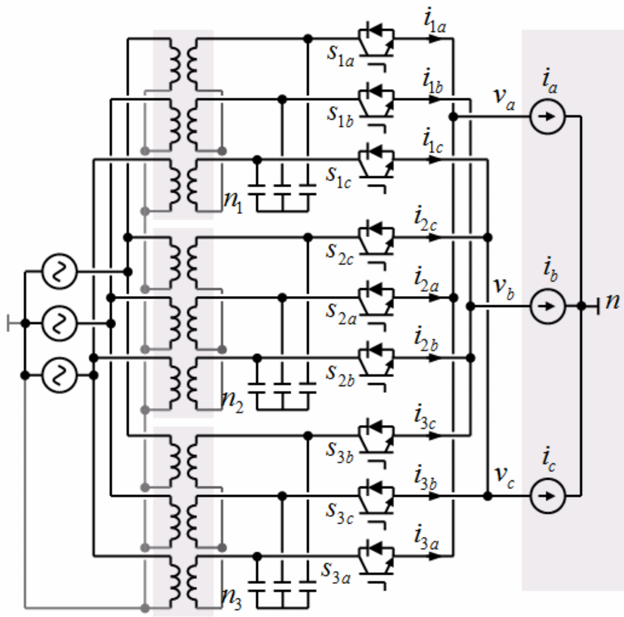

Fig. 3. Additional details about the implementation for the converter in Fig. 1. Capacitors decouple the transformer's leak inductance to behave as a voltage source.

III. Simplified Vector Switching Converter

This section explains the principle of the Simplified Vector Switching Converter or SVeSC, which may substitute the VeSC, reducing the number of driven switches, which are very expensive in high power applications. Fig. 4 depicts a three-phase **Nx1** simplified vector switching converter.

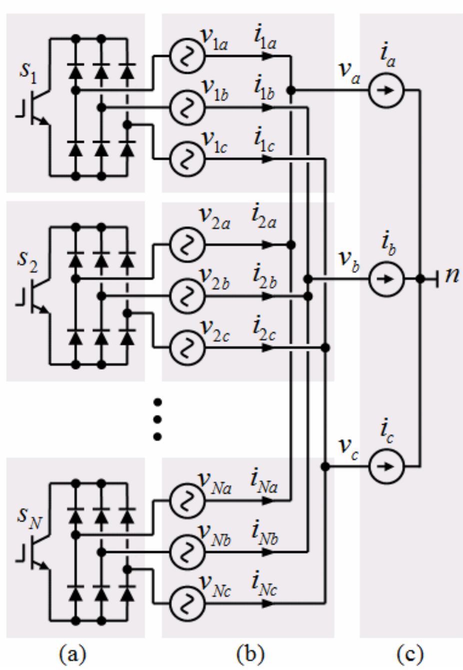

Fig. 4. **Nx1** VeSC (a) three phase switches (b) voltage inputs (c) output

The operating principle will be explained by a three-phase **2x1** SVeSC, Fig. 5.

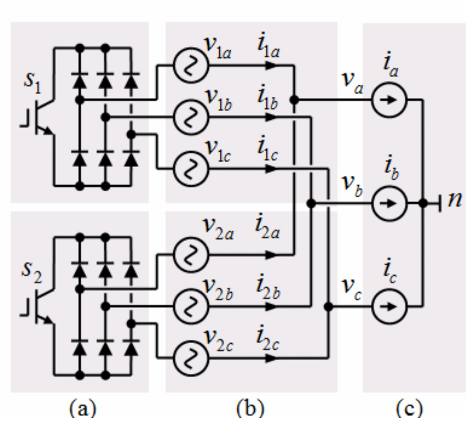

Fig. 5. Three-phase **2x1** simplified vector switching converter (a) three-phase switches (b) three-phase input voltages (c) three-phase output

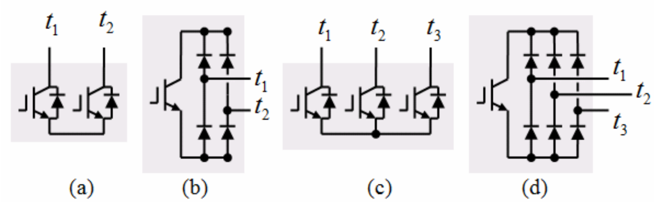

Fig. 6. (a) and (b) two-ports bidirectional switches (c) and (d) three-ports bidirectional switches

Fig. 4(a), Fig. 5(a) and Fig. 6 show the three-phase bidirectional switches, being the basis of the converter. The matrix converter is based on two-ports bidirectional switches, as the one shown in Fig. 6(a)-(b) [26].

Some other AC-link converters, are based on three-port bidirectional switches. Such converters are simpler and cheaper but they can only multiply the voltage by a duty cycle using PWM; they are derived from the conventional DC-DC converters, and can be called with the same names: buck, boost, buck-boost, Cuck, etc. [27-28]. Those three-ports bidirectional switches are illustrated in Fig. 6(c)-(d). As the DC-DC converters, the PWM is asynchronous and the phase angle of the AC signals doesn't have any effect on the converter operation.

According to the switching state of S_1 and S_2 in Fig. 5, the converter exhibits two equivalent circuits, Figs. 7-8.

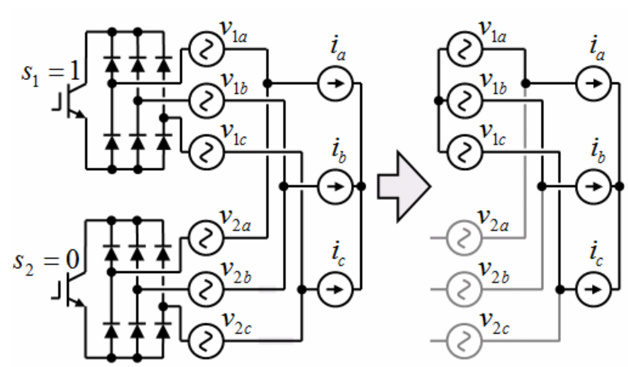

Fig. 7. Equivalent circuit when S_1 is *on* and S_2 is *off*.

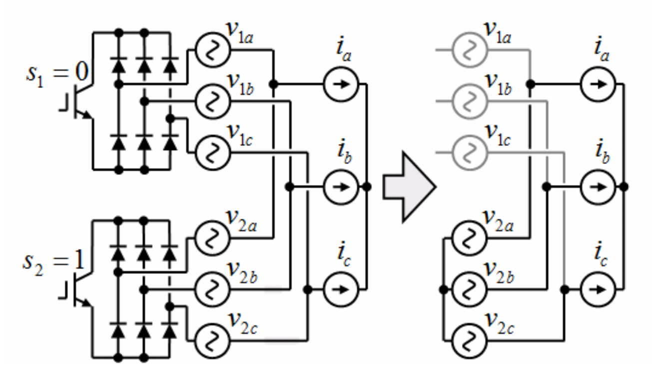

Fig. 8. Equivalent circuit when S_1 is *off* and S_2 is *on*

From Figs. 5 and 7, when $S_1 = 1$ and $S_2 = 0$:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} v_{1a}(t) \\ v_{1b}(t) \\ v_{1c}(t) \end{bmatrix} \tag{5}$$

and

$$\begin{bmatrix} i_{ia}(t) \\ i_{ib}(t) \\ i_{ic}(t) \end{bmatrix} = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{6}$$

Equivalent equations can be deduced when S2 is *on* and S1 is *off*. Defining t_{1on} as the time when S_1 is *on*, t_{2on} as the time when S_2 is *on*, and T as the total switching period, so that duty cycles become:

$$d_1 = \frac{t_{1on}}{T}; \qquad d_2 = \frac{t_{2on}}{T} \tag{7}$$

In terms of PWM control this can be expressed by,

$$\frac{t_{1on} + t_{2on}}{T} = d_1 + d_2 = 1 \tag{8}$$

The average load voltage can be expressed in terms of those switches' duty cycles and the input voltages as:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} v_{1a}(t) & v_{2a}(t) \\ v_{1b}(t) & v_{2b}(t) \\ v_{1c}(t) & v_{2c}(t) \end{bmatrix} \begin{bmatrix} d_1(t) \\ d_2(t) \end{bmatrix} \tag{9}$$

The average current for each input voltage source can be expressed in terms of duty cycles and load current as:

$$\begin{bmatrix} i_{ia}(t) \\ i_{ib}(t) \\ i_{ic}(t) \end{bmatrix} = d_i \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{10}$$

for $i = 1, 2$. Equations (9) and (10) are equivalent to (3) and (4) and they can be extended.

It is important to show that the converter in Fig. 5 cannot be extended to any number of loads. However, it can be extended to any number of input voltages, this is the major constraint of the SVeSC, which can achieve simpler topologies for FACTS devices and power conditioners but it cannot be extended to complex interconnections.

Equations (9) can be extended to the converter in Fig. 4 as:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} v_{1a}(t) & v_{2a}(t) & v_{Na}(t) \\ v_{1b}(t) & v_{2b}(t) \cdots & v_{Nb}(t) \\ v_{1c}(t) & v_{2c}(t) & v_{Nc}(t) \end{bmatrix} \begin{bmatrix} d_1(t) \\ d_2(t) \\ \vdots \\ d_N(t) \end{bmatrix} \tag{11}$$

and (10) holds for $i = 1, 2 \ldots N$.

In general, for the same converter's topology the SVeSC utilizes less IGBTs and more diodes. The number of IGBTs in the SVeSC compared with the VeSC is:

$$IGBTs_{SVeSC} = \frac{IGBTs_{VeSC}}{3} \tag{12}$$

while the number of diodes becomes:

$$Diodes_{SVeSC} = 2Diodes_{VeSC} \tag{13}$$

IV. Ξ CONTROLLER

As the VeSC, the SVeSC can be employed in applications such as custom power within distribution system and power flow control in the transmission system with fewer switches. The limitation of the SVeSC against the conventional VeSC is that only the number of three-phase voltage sources may be increased to any number. The number of three-phase current sources is only one, but this can be a limitation for some application with complex interconnection.

The SVeSC is cheaper and easier to implement and should be selected if is possible. In this paper the simplification of the Ξ and the Γ controllers is studied, both are FACTS controllers developed based on the AC-link approach [15, 16, 20].

The main function of a series compensator is to behave as a three-phase variable capacitor. In the DC link approach the SSSC and the DVR can provide this function. In the AC-link approach, the Ξ controller has been proposed, similarly to the TCSC, the Ξ controller is based on a pure capacitive reactance controlled by PWM.

By connecting and disconnecting capacitors to the system, and controlling the time, it is possible to achieve the desired principle. Fig. 9 depicts a realization of the Ξ controller proposed in [16] with the single phase equivalent circuit. Fig. 10 shows the realization proposed in [15]. Fig. 11 is the vector converter representation of the Ξ controller, and Fig. 12 displays this simplified controller.

The realization of [15], Fig. 10, exhibits a special arrangement which uses only 4 driven switches and doesn't need snubbers across the switches, thanks to the capacitors and resistors connected to the switches.

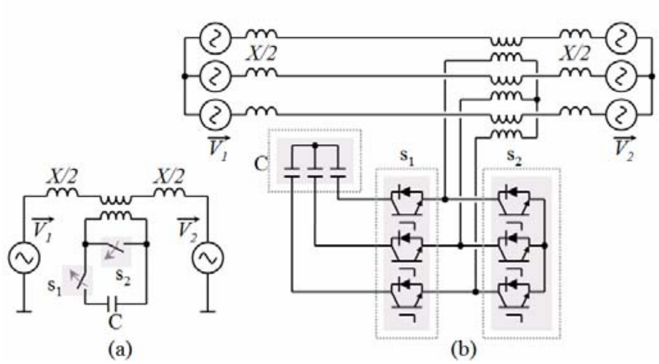

Fig. 9. Ξ controller (a) single phase circuit (b) three-phase circuit [16]

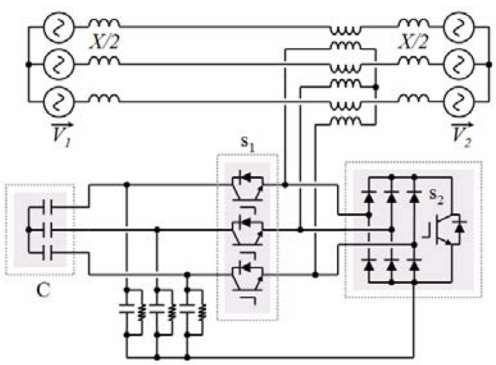

Fig. 10. Other realization of the Ξ controller [15]

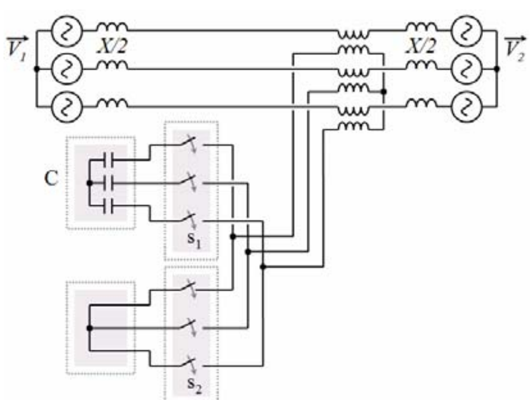

Fig. 11. Vector switching converter representation of the Ξ controller

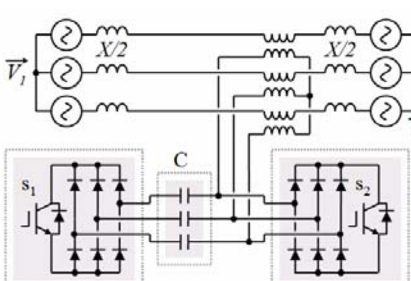

Fig. 12. SVeSC based Ξ controller

In all schematics, S_1-S_2 are complementary, allowing the line current to flow through the capacitor, or creating a free path or free wheeling for the line current when the capacitor is disconnected, Figs. 9-12.

Ξ controllers present different power stages, although they operate under the same principle and their equivalent circuits, for both switching states, are similar. Fig. 11 shows the VeSC representation of the Ξ controller. It can be analyzed as two three-phase stiff voltage sources connected through a **2x1** three-phase vector switching converter to a series connected transformer (which behaves as a current source). One of the voltage sources is the compensating capacitor, which voltage depends on the line current, the duty cycle and the transformer ratio.

The representation as a SVeSC can be easily obtained, from the representation as a VeSC, and then the theory explained in section II and III of this paper can be applied to this arrangement.

V. Ξ CONTROLLER'S SIMULATION

Simulations of the simplified Ξ controller are detailed in the following, to prove the viability of the proposed topology. The simulation scenario is the active power flow control between two three-phase buses.

Fig. 13 depicts the circuit with the close loop control block diagram for controlling the active power flow from **V1** to **V2**. The simulation parameters are: **V1** is the sending bus and **V2** is the receiving one, both have 220V RMS line-to-line with 30° as angular difference. Line inductance is 26.52 mH (10Ω), the coupling transformer turn's ratio is 1:1, and the compensating capacitors are 1.32mF (each).

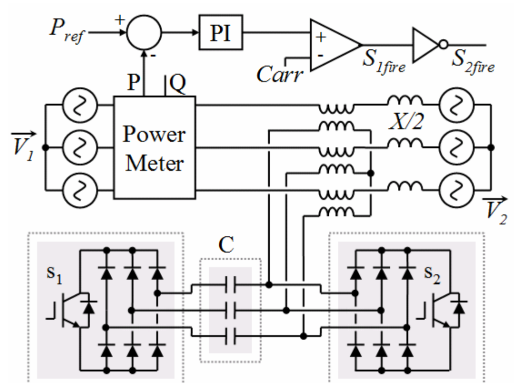

Fig. 13. Simulated circuit

Fig 14 illustrates the power meter based on Clarke's transformation (only the active power flow is controlled).

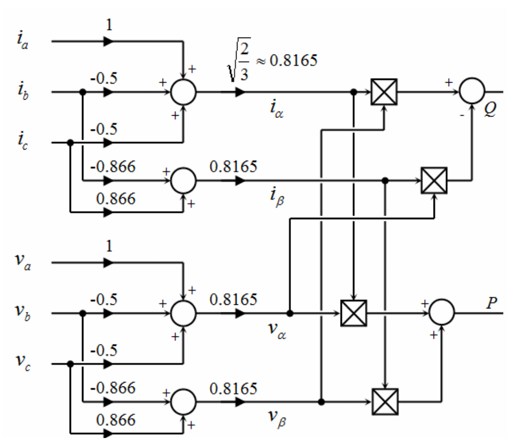

Fig. 14. Power Meter block by the static reference frame

Figs. 15-16 are the system response in face of a 5% step down variation on voltage **V1** (sending bus). For the non-compensated system the line current decreases a little bit, which makes that the active power diminishes and attains a lower value at steady state, while the compensated line increases the current to reach the previous steady state power in some cycles.

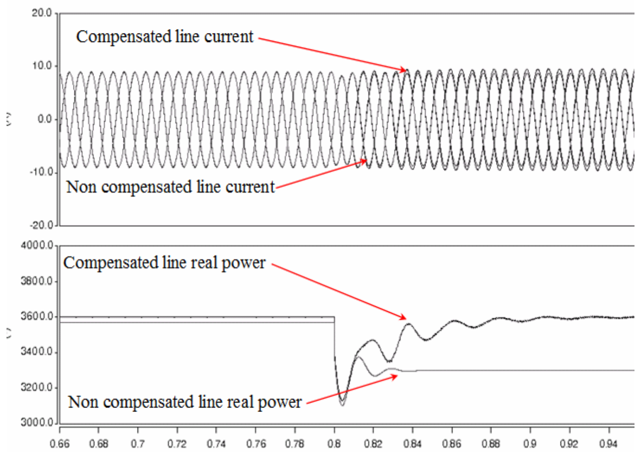

Fig. 15. Current and active power for the compensated and non-compensated system under a disturbance

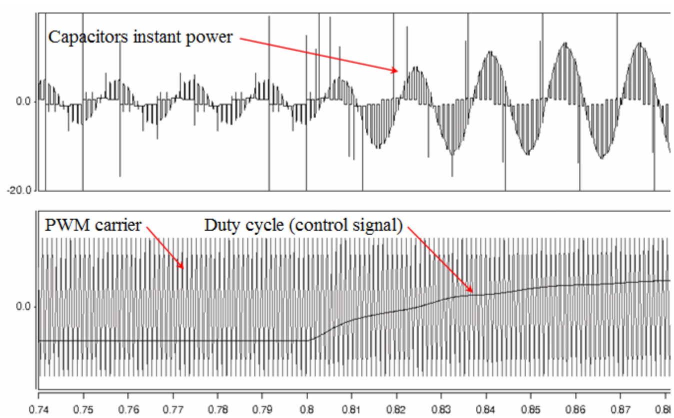

Fig. 16. Capacitors' instant power and duty cycle with the PWM carrier during the disturbance

Another advantage of the proposed topology is that the energy stored in parasitic elements is also rectified when the switch turns off and during the dead time. This is neglected in the simulation but in actual implementations a similar over-voltage snubber circuit used in VSC (based on one diode, one resistor, and one capacitor) may be utilized in the diode bridges, Fig. 17.

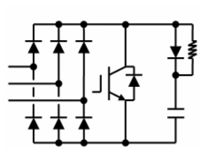

Fig. 17. One snubber circuit is employed for each switch in the proposed simplified topologies.

Thus, the proposed configuration is able to control the active power flow in a three-phase transmission line by using only two driven switches, whose number is important because they are pretty expensive in high power applications.

VI. Some Other Applications

As it can be noticed from the proposition, the key point lies in the fact that a three-phase "Y" connection may be opened by a three-phase bidirectional switch which consists in a diode full bridge and a transistor. In this way, configurations of transformers based compensators, such as tap changers or the Sen Transformer's family [8], can be simplified if it is possible to configure them in "*Y*" connected transformers.

The second proposed application is the Γ controller, which is an AC-link Power Flow Controller similar to the DC-link UPFC. It was proposed in [19] based on a **4x1** three-phase vector switching converter. Another possible structure is the one shown in Fig. 18, which is based on a **3x1** VeSC. Fig. 19 schematizes the simplified Γ controller.

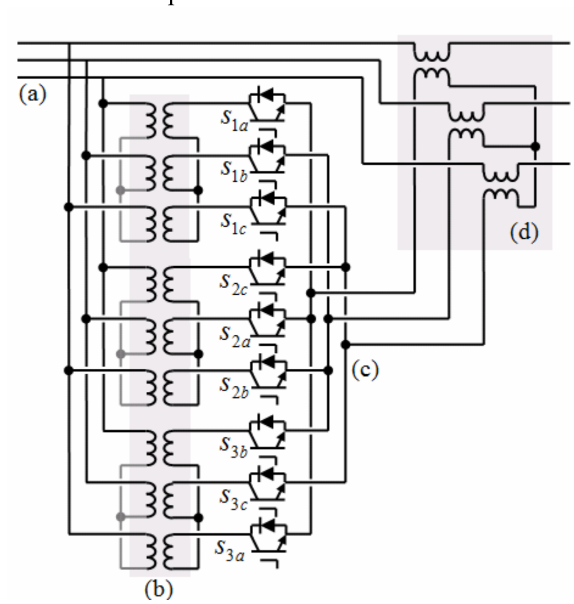

Fig. 18. VeSC based UPFC (a) transmission line (b) phase shift transformers (c) **3x1** three-phase VeSC (d) series injection transformer.

Fig. 19 shows the SVeSC Γ controller based on a **3x1** converter, in the same way as the conventional VeSC, it requires the phase shifting transformers to get the isolated three-phase voltage sources, which feeds the series injection transformer through the power semiconductor arrangement.

Fig. 20 illustrates the realization of a two-switches based three-phase tap changer. This one can be PWM controlled to achieve voltage control, and it can include more taps with one driven switch for each one.

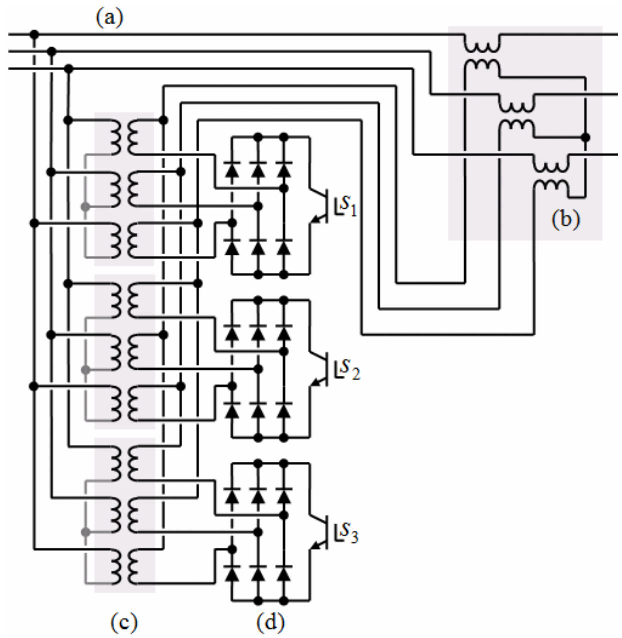

Fig. 19. SVeSC based UPFC (a) transmission line (b) series injection transformer (c) phase shift transformers (d) **3x1** three-phase SVeSC.

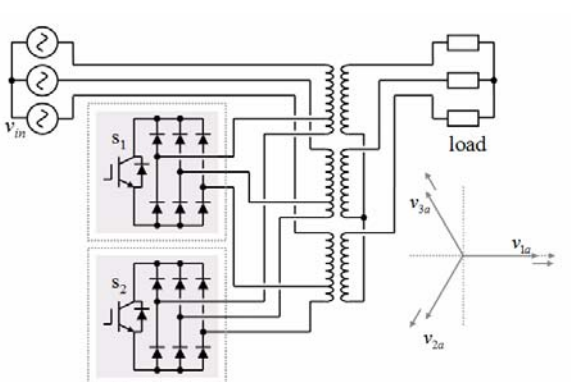

Fig. 20. Two driven switches tap changer, one driven switch is used for each tap. A secondary tap configuration can be derived in the same way.

VII. Conclusions

This paper introduces the Simplified Vector Switching Converter SVeSC as a new member of the Vector Converter's family. This topology is simpler and cheaper than the VeSC and may be used for developing simple topologies for FACTS controllers and Power Conditioners with a reduced number of switches, increasing the reliability and cost reduction. It is shown how the AC-link FACTS controllers such as the Γ and Ξ controllers can be implemented with the SVeSC.

The AC-link converters bring the promise to reduce the size, cost, and the number of driven switches (increasing the reliability) in power conditioners and FACTS controllers. Several new FACTS devices and power conditioners have been proposed in the last decade based on such technology.

Some advantages, compared to the conventional voltage source converter-based devices are: (*i*) it does not have an energy-stored element; (*ii*) the controller does not need a PLL nor trigonometric calculations, which made the converter insensitive to frequency variations, improving the stability; (*iii*) the controller requirements are much cheaper than the conventional devices which can be implemented in a low cost microcontroller; (*iv*) the power stage requires fewer switches, which improve the reliability.

The key point of the proposed simplification is that a three-phase Y transformer can be opened at the neutral point with only one driven switch, using a three-phase bidirectional switch consisting on one diode's full bridge and one transistor. In this way all configuration of transformer based compensators, such as tap changers or the Sen Transformer's family [8], may be simplified if it is possible to configure them in *"Y"* connected transformers. The snubber circuits are simple and cheap.

To verify the viability of the proposed SVeSC, simulation results in a SVeSC based Ξ controller for active power flow control are provided.

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