A Novel Precise Steps-Based Independent Active and Reactive Power Flow Controller

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Abstract**—** A novel precise-steps based independent active and reactive power flow controller (PSPFC) is proposed in this paper. The PSPFC is a phase-shifting and voltage-regulating device in one unit. In addition to its main windings and load tap-changing switches (LTCs), the PSPFC combines fractionally rated windings and thyristor switches. The PSPFC can provide controllable quadrature and direct voltages; and control active and reactive power flow simultaneously or selectively. In this paper, first, configuration of the PSPFC is revealed; then, ratings of windings, LTCs, and thyristor switches are determined. Following, the PSPFC is modelled in MATLAB/SIMULINK and connected to a two-bus two-machine system to investigate its steady-state behavior, power flow control limits, control preciseness, and independent power flow control capability. Based on the results, as compared to combined action of phase-shifting transformer (PST) and voltage-regulating transformer (VRT), the PSPFC is advantageous. With aid of the fractionally rated components, PSPFC possesses improved response and precise steps with the wide control range of PST and VRT retained. Consequently, PSPFC ensures not only a highly reduced control-error and smooth control-action, but also a wider power flow control range and a more independent power flow control capability. Operation of PSPFC is flexible; and action of the precise steps is fast. PSPFC is thus suitable for applications that require fast response. Operational characteristics of PSPFC are closely comparable to those of the Unified Power Flow Controller (UPFC). However, unlike the UPFC, PSPFC does not create any harmonics facilitated by its thyristor ON-OFF control.

Keywords**—** Flexible AC transmission systems, phase shifting transformer, power grid flexibility, power flow control, voltage regulating transformer.

I. INTRODUCTION

Phase shifting transformer (PST) and voltage regulating transformer (VRT) [1], which are based on mechanical tap-changing switches, are simple in construction. PST is an effective active power flow controller (PFC) [2], [3] while VRT is an effective reactive PFC [3], [4]. More recently, Sen Transformer (ST) is developed by Sen and Sen [5]. ST is economically and technically attractive as it simultaneously or selectively performs both PST and VRT functions in one unit [6], [7]. However, similar to PST and VRT, ST has limited operating points and large steps when designed to have a wide control range, non-preventable control-error, and relatively slow response rate- in the range of two seconds to switch between any two adjacent operating points- for applications that need fast response [7]. Versions of PSTs and VRTs that replace the mechanical tap-changing switches by thyristors have enhanced response rate, but, still suffer from other limitations. These limitations do not always enable fulfilling most favorable operating state of the grid. On the other hand, flexible AC transmission systems (FACTS) devices are the most flexible PFCs [8], [9]. Within their control range, they neither have response rate nor limited operating points limitation. Among FACTS devices, unified power flow controller (UPFC) is the most versatile. It can simultaneously or selectively control active and reactive power flow. However, practical installation of the UPFCs is limited [10] due to the high investment costs [11], [12]. The comparable ST can be more widely used for many utility applications [13]. Two main transformer-based static phase shifters (SPS) are type-B and type-B1 [14], [15] which operate

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discretely but with precise steps. Their steps are precise owing to their three voltage level windings. However, as they are only based on fractional three voltage levels, they have a small control range. On the other hand, type-B SPS can only control active power flow [15].While type-B1 SPS can control both active and reactive power flow [15], it has two excitation transformers to provide essential in-phase and quadrature voltages for that purpose. Introduction of fractionally rated components to conventional PFCs, such as PST, VRT, and ST, is significantly beneficial. Controllable network transformer (CNT) [16] with fractionally rated components is an effective PFC [17] that can independently and precisely control active and reactive power flow. However, while wide active power flow control capability is highly desired, active power flow limit of CNT is typically half that of reactive power flow [7].

Based on above review, a device that combines most merits of considered PFCs in a single unit is highly desired. In light of that, a precise steps based power flow controller (PSPFC) that retains most advantages of the available PFCs is proposed in this paper. This paper first introduces configuration of the PSPFC, determines ratings of windings, LTCs, and thyristor switches, and presents PSPFC operation principle. Then, it demonstrates its independent active and reactive power flow control capability in an equivalent two-bus two-machine system. The results revealed effectiveness of the proposed PFC, its fine steps and thus more flexible operation, and its independent active and reactive power flow control capability.

II. BASIC CONFIGURATION OF PSPFC

Arrangement of LTC based PST is modified; and fractionally rated windings and thyristor switches are added to build the PSPFC. Fig. 1 shows a PSPFC connected to a transmission line. The PSPFC mainly consists of two transformers. These are the excitation transformer (shunt) and the injection transformer (series).

Each of these transformers is composed of three parts, namely the main PFC (PFC_{Ma}), the one-third PFC (PFC_{Th}), and the one-ninth PFC (PFC_{Ni}). The PFC_{Ma} has some tap positions in its excitation transformer's secondary side (4 tap positions are considered in this paper). Contrarily, as the case in the type-B and type-B1 SPSs, each of PFC_{Th} and PFC_{Ni} has only two terminals in the excitation transformer's secondary side. In Fig. 1, PFC_{Ma}'s windings are in blue; and their terminals are assigned number (1); PFC_{Th}'s windings are in orange; and their terminals are assigned number (3); and finally, PFC_{Ni}'s windings are in purple; and their terminals are assigned number (9).

Fig. 2 shows components of shunt transformer of PFC_{Ma}, PFC_{Th}, and PFC_{Ni}. In Fig. 2a, the boxes combine primary and secondary windings of PFC_{Ma}'s excitation transformer as well as LTCs. Contents of one box are shown in details in Fig. 3a.

Each of S_1, S_2, S_3, and S_4 is an LTC. No windings are combined in the boxes in Fig. 2b and c. Each of these boxes contains thyristor switches, which are shown in details in Fig. 3b.

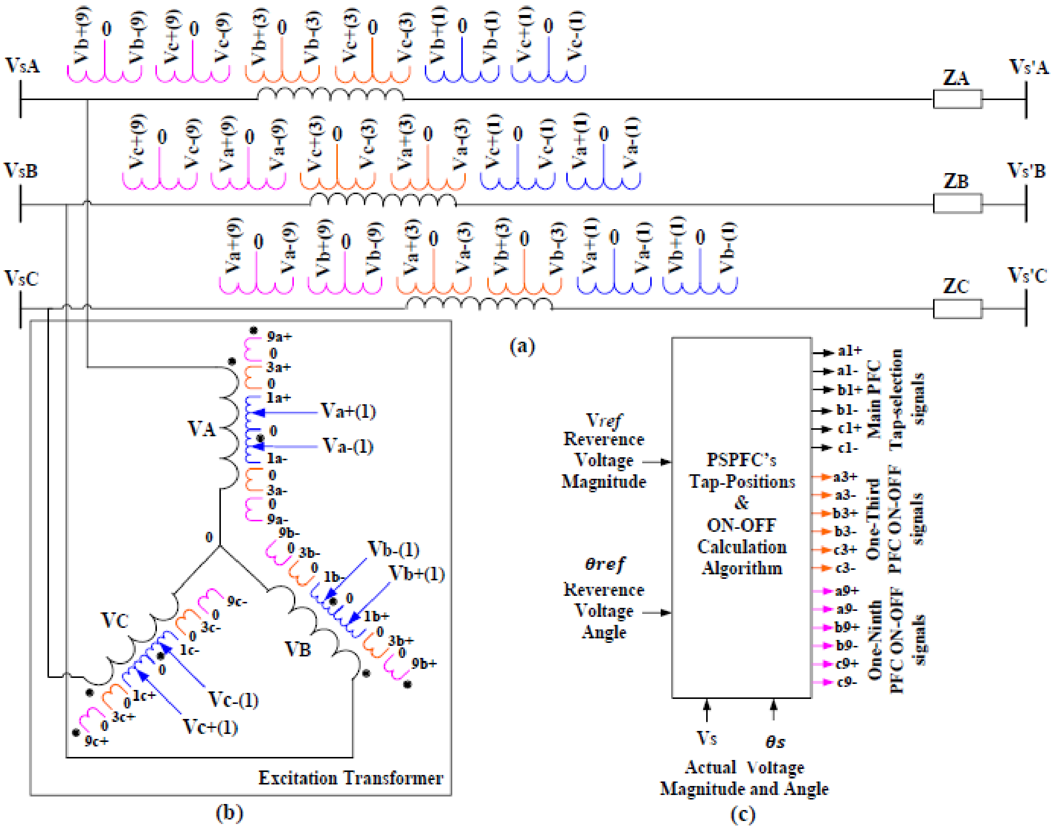

Fig. 1. a) A transmission line equipped with series transformer, b) PSPFC excitation transformer windings arrangement and c) controller block

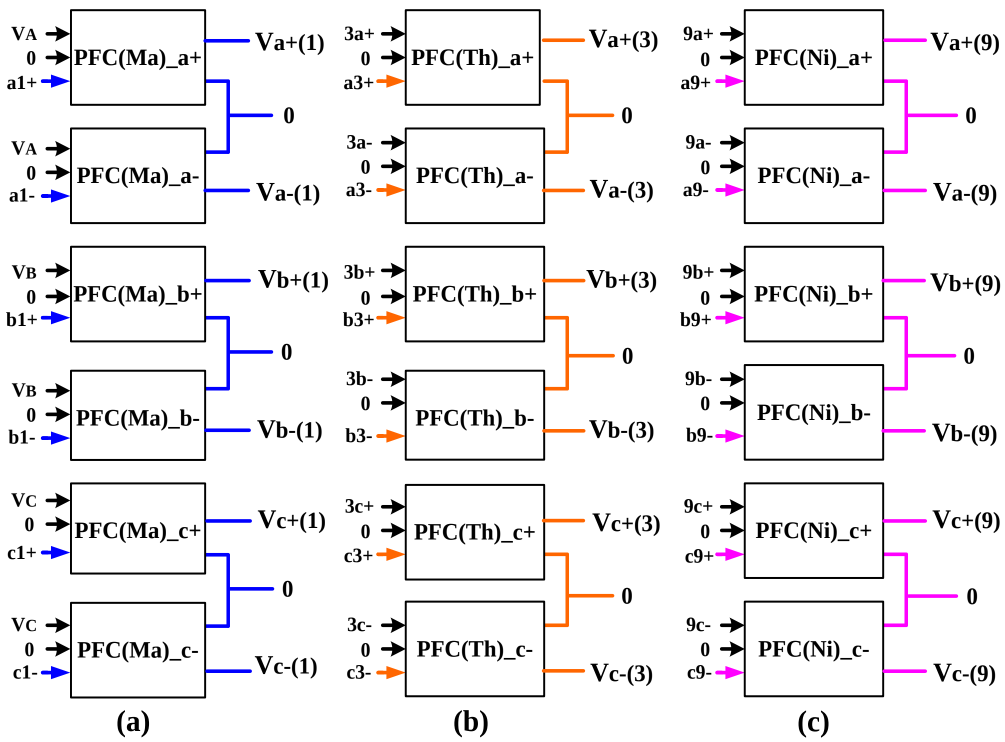

Fig. 2. Parts of a) PFCMa, b) PFCTh and c) PFCNi

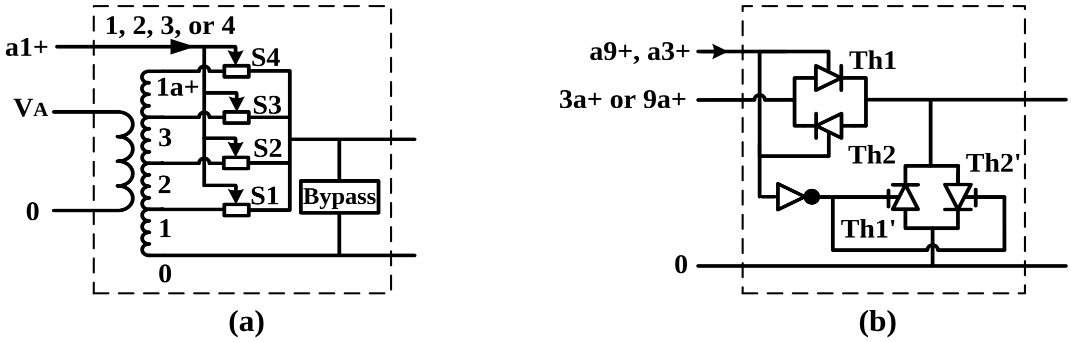

Fig. 3. a) PFCMa windings and LTCs and b) PFCTh and PFCNi boxes components

III. Ratings of PSPFC Components

Voltage ratings of the windings of *PFCMa* are determined first. Referring to Fig. 4a, and considering the step voltage of the *PFCMa* 0.1 pu voltage, corresponding essential voltage of windings *c* and *b* is obtained as depicted in Fig. 4b. Assigning *x* to voltage of windings *c* and *b* of the PFC_{Ma}, value of *x* is obtained as given by (1).

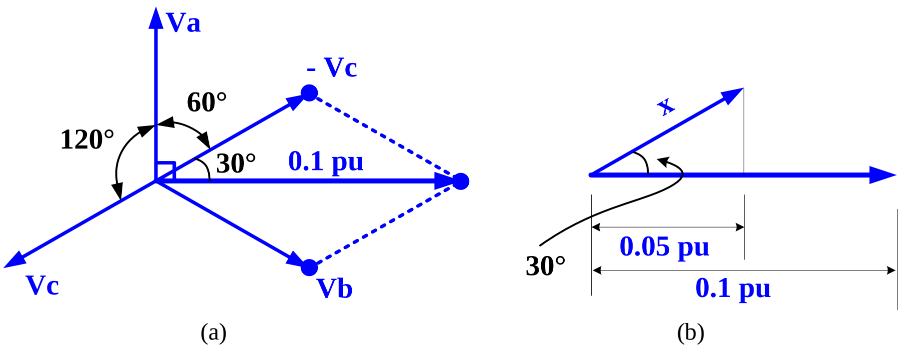

Fig. 4. Determination of voltage rating of windings of the PFCMa

$$x = 0.05 / \cos 30 = 0.057735\, pu \tag{1}$$

With a PFC_{Ma} steps size of 0.1 pu quadrature voltage, essential ratings of compensation quadrature voltages of PFC_{Th}, and PFC_{Ni} are 0.03333 pu, and 0.01111 pu, respectively. These voltages provide equally spaced points between step points of PFC_{Ma} in quadrature to transmission line voltage. Ratings of the six phase voltages that can result in these quadrature axis voltages are found geometrically as shown in Fig. 5. In view of compensation of phase "A" of a transmission line, and considering the depicted three phase voltage vectors, and the quadrature voltage, Fig. 5 shows possible quadrature-direct voltage that each of PSPFC parts can provide. As obtained geometrically, it is seen that the rating of each winding of PFC_{Ma}, for a step of 0.1 pu voltage, is only 0.057735 pu voltage. Also, ratings of PFC_{Th}'s and PFC_{Ni}'s windings are only 0.019245 pu, and 0.006415 pu to provide the 0.03333 pu, and 0.01111 pu voltage, respectively. Fig. 6 shows direct and direct-quadrature voltage operating points that each PFC part can provide. For PFC_{Ma}, to provide up to 4 steps (0.4 pu voltage in quadrature to the transmission line voltage), Fig. 7 shows full essential voltage rating of windings. Voltage rating of thyristors of PFC_{Th}, and PFC_{Ni} is only 0.019245 pu, and 0.006415 pu of one phase of the transmission voltage.

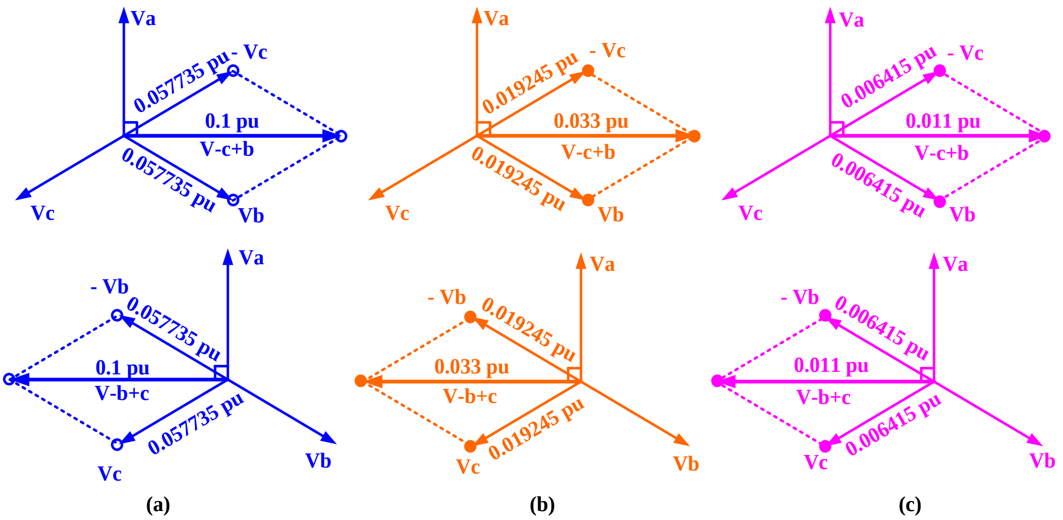

Fig. 5. Quadrature and direct-quadrature voltage operating points and ratings of windings and switches of a) PFCMa (for one step), b) PFCTh and c) PFCNi, and operating points (the dots)

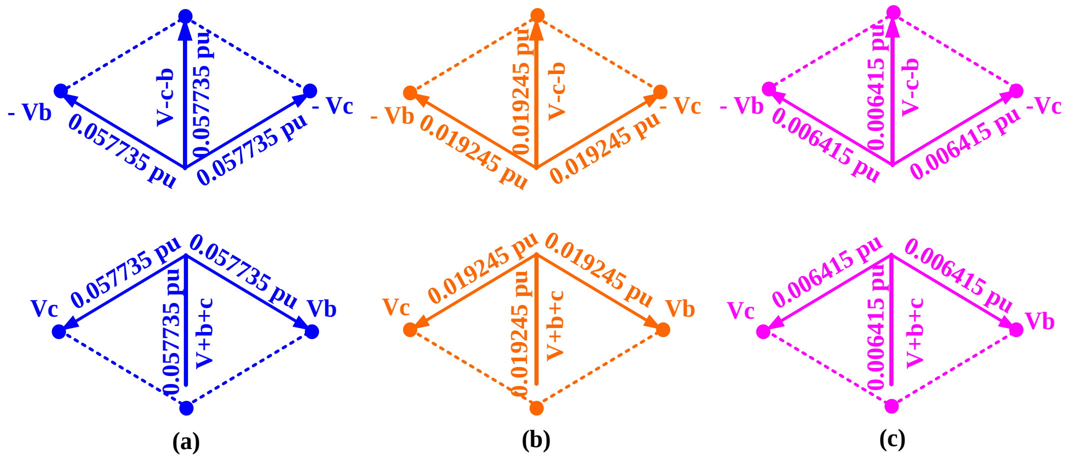

Fig. 6. Direct and direct-quadrature voltage operating points that each PFC part can provide:
a) PFCMa (one step), b) PFCTh and c) PFCNi

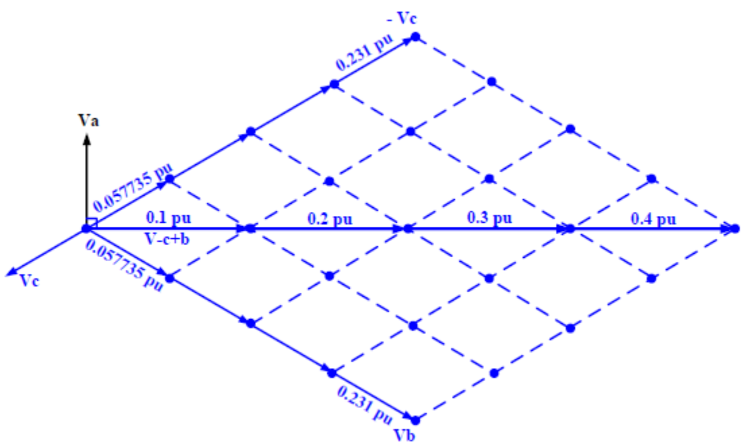

Fig. 7. Voltage rating of windings and switches of PFCMa to provide up to four step (0.4 pu) quadrature voltage (Only one-quarter of PFCMa's operating area is shown)

Only one-quarter of the operating area of the PSPFC is shown in Fig. 7. As obtained geometrically, essential rating of PFC_{Ma} windings is only 0.231 pu of transmission line voltage. This arrangement facilitates PFC_{Ma} to provide 0.231 pu direct voltage which can be in-phase or out-of-phase. Voltage ratings of LTCs of PFC_{Ma} are 0.057735 pu for first step; 2×0.057735 pu for second step; 3×0.057735 pu for third step; and 4×0.057735 pu for fourth step.

IV. OPERATION PRINCIPLE OF PSPFC

The proposed PSPFC provides three different compensation voltages. These are PFC_{Ma}'s voltage ($V_{PFC(Ma)}$), PFC_{Th}'s voltage ($V_{PFC(Th)}$), and PFC_{Ni}'s voltage ($V_{PFC(Ni)}$) which are all step-wise based. Thus, PSPFC provides a mix of stepped voltages that may be one, or a combination of two or three of these voltages according to the needs. $V_{PFC(Ma)}$ can be 0, ±0.1, ±0.2, ±0.3, or ±0.4 pu; $V_{PFC(Th)}$ can be 0 or ±0.0333 pu; and $V_{PFC(Ni)}$ can be 0 or ±0.01111 pu. These voltages' contents can be additive or subtractive, leading or lagging simultaneously or selectively to voltage of transmission line to be compensated, and can be in each of possible six directions. As these voltages act in series to each other, many possible resulting voltage magnitudes and angles can be realized. In this section, operation principle of PSPFC is introduced taking compensation of phase 'A' of transmission line as an example. In view of Fig. 5, when tap points of phases $-V_b$ and V_c (or V_b and $-V_c$) of PFC_{Ma} are symmetrically closed, PFC_{Ma} provides a quadrature voltage that advances (or retards) the transmission voltage phase angle. Similarly, when thyristor pairs of phases $-V_b$ and V_c (or V_b and $-V_c$) of PFC_{Th} and PFC_{Ni} are closed, PFC_{Th} and PFC_{Ni} provide fractional quadrature voltages which slightly advance (or retard) transmission voltage phase angle. On the other hand, considering Fig. 6, when tap points of phases $-V_b$ and $-V_c$ (or V_b and V_c) of PFC_{Ma} are symmetrically closed, PFC_{Ma} provides a direct voltage that increases (or decreases) transmission voltage magnitude. Similarly, when thyristor pairs of phases $-V_b$ and $-V_c$ (or V_b and V_c) of PFC_{Th} and PFC_{Ni} are closed, PFC_{Th} and PFC_{Ni} provide fractional direct voltages that slightly increase (or decrease) transmission voltage magnitude. Non-symmetrical switching of PFC_{Ma}'s tap points (switching of second tap of $-V_c$ and first tap of V_b in Fig. 5 (a) for instance) and switching of one winding of PFC_{Th} or PFC_{Ni} result in a mix of quadrature and direct voltages. Quadrature voltage causes dominant phase shift and relatively dominant active and slight reactive power flow control. Direct voltage causes dominant voltage magnitude control and relatively dominant reactive and slight active power flow control. Similarly, phases 'B' and 'C' of transmission line are compensated by voltages ($+V_a/-V_a$ and $+V_c/-V_c$) and ($+V_a/-V_a$ and $+V_b/-V_b$) of PFC_{Ma}, PFC_{Th}, PFC_{Ni} respectively.

To activate an operating point of PSPFC, a tap point of PFC_{Ma} is selected; and suitable actions of PFC_{Th} and PFC_{Ni} are activated by turning on appropriate thyristor pairs. When active power is controlled by a quadrature voltage action, reactive power follows circuit rules, and vice-versa. However, PSFPC has a high capability of independent active and reactive power flow control. Independency is high owing to the precise steps action of PSPFC. Vector diagrams of Fig. 8 show two different examples of PSPFC's compensation voltage. As can be seen, these voltages result from possible combinations of voltages of PFC_{Ma}, PFC_{Th}, and PFC_{Ni}.

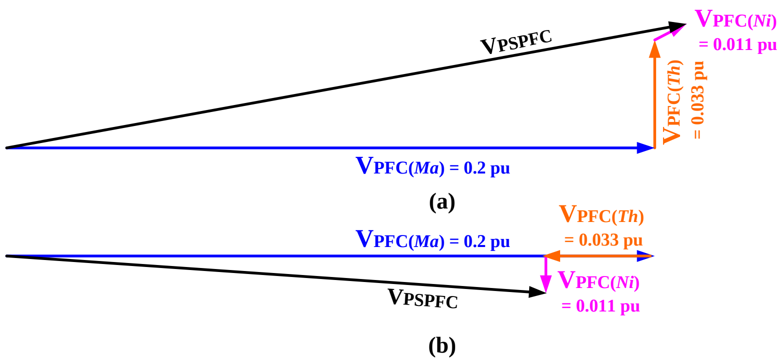

Fig. 8. Two examples of PSPFC's compensation voltage: a) VPFC(Ma)= 0.2 pu (0^o), VPFC(Th)= 0.033 pu (90^o), and VPFC(Ni)= 0.011 pu (30^o), b) VPFC(Ma)= 0.2 pu (0^o), VPFC(Th)= 0.033 pu (180^o), and VPFC(Ni)= 0.011 pu (-90^o)

Augmentation of PFC_{Th} to PFC_{Ma} results in two intermediate steps between that of PFC_{Ma}. Similarly, augmentation of PFC_{Ni} to PFC_{Th} and PFC_{Ma} results in two intermediate steps between that of PFC_{Th}. Accordingly, eight steps are provided between any two steps of PFC_{Ma}. As can be seen in Fig. 1, arrangement of secondary windings of excitation transformer enables providing all six phase voltages (V_a, V_b, V_c, $-V_a$, $-V_b$, and $-V_c$), which are 60^o apart of each other. Within limits of PFC_{Ma} of Fig. 7, fractional compensation voltages of PFC_{Th} and PFC_{Ni} provide many possible combinations of compensation voltage. In PSPFC, the gap between each two operating points of PFC_{Ma} is filled by possible eight operating points in all directions. Fig. 9 shows full potential operating points of only most left corner of one quarter operation area of PCPFC. This figure shows that each four operating points of PFC_{Ma} are converted to 100 in the considered PSPFC (the dots in orange and purple) by aid of PFC_{Th} and PFC_{Ni}. By-pass switches of PFC_{Ma}, PFC_{Th}, and PFC_{Ni} are turned ON selectively or simultaneously when no compensation voltage is needed, or when a PFC part fails mainly to maintain reliability.

In Fig. 9, blue dots that are located on the blue horizontal line are realized by symmetrically switching tap points of PFC_{Ma}. Non-symmetrical switching realizes the points that are above or below the horizontal line. Similarly, in most left corner, orange and purple dots, which are located on the blue horizontal line, are achieved by switching an appropriate pair of voltages of PFC_{Th} and $PFC_{Ni.}$ Conversely, the points that are above or below are obtained by switching one winding of PFC_{Th} and/or PFC_{Ni}.

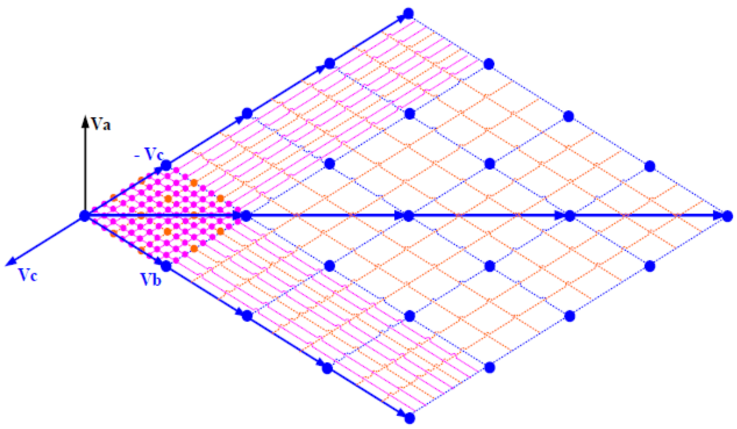

Fig. 9. Quarter of PSPFC's control area showing only full possible operating points of most left corner

Vector sum of voltages $V_{PFC(Ma)}$, $V_{PFC(Th)}$ and $V_{PFC(Ni)}$ provides PSPFC's compensation voltage (V_{PSPFC}) as given by (2):

$$V_{PSPFC} = V_{PFC(Ma)} + V_{PFC(Th)} + V_{PFC(Ni)} \tag{2}$$

Then, when a PSPFC is connected at the sending end of a transmission line, an effective sending end voltage is given by:

$$V_S^{'} = V_S + V_{PSPFC} \tag{3}$$

Real and reactive power (P_R and Q_R) at the receiving-end of a transmission line are given by (4) and (5):

$$P_R = \frac{V_S^{'} V_R}{X_L} \sin \delta^{'} \tag{4}$$

$$Q_R = \frac{V_S^{'} V_R}{X_L} \left(\cos \delta^{'} - \frac{V_R}{V_S^{'}} \right) \tag{5}$$

where $V_S^{'}$ is effective sending end voltage; V_R receiving end voltage; X_L transmission line and PSPFC's series reactance; and $\delta^{'}$ effective transmission line angle.
The phase angle of effective sending end voltage is given by the algebraic summation shown in (6):

$$\psi_{PSPFC} = \psi_{PFC(Ma)} + \psi_{PFC(Th)} + \psi_{PFC(Ni)} \tag{6}$$

where $\psi_{PFC(Ma)}$, $\psi_{PFC(Th)}$, and $\psi_{PFC(Ni)}$ are phase angle shift, which is caused by PFC_{Ma}, PFC_{Th}, and PFC_{Ni}, respectively. Then, effective transmission angle $\delta^{'}$ is given by:

$$\delta^{'} = \delta + \psi_{PSPFC} \tag{7}$$

where δ is the natural (non-controlled) transmission angle.
PSPFC's voltages $V_{PSPFC(B)}$ and $V_{PSPFC(C)}$, are injected to phase 'A' of the transmission line through an injecting transformer. $V_{PSPFC(B)}$ composes $V_{PFC(Ma)(b)}$, $V_{PFC(Th)(b)}$, and $V_{PFC(Ni)(b)}$; and $V_{PSPFC(C)}$ composes $V_{PFC(Ma)(c)}$, $V_{PFC(Th)(c)}$, and $V_{PFC(Ni)(c)}$. Referring to (2) and Fig. 1, $V_{PFC(Ma)(b)} = V_{b+(1)}$, *or* $V_{b-(1)}$; $V_{PFC(Th)(b)} = V_{b+(3)}$, *or* $V_{b-(3)}$; and $V_{PFC(Ni)(b)} = V_{b+(9)}$, *or* $V_{b-(9)}$. Similarly, $V_{PFC(Ma)(c)} = V_{c+(1)}$ or $V_{c-(1)}$; $V_{PFC(Th)(c)} = V_{c+(3)}$ or $V_{c-(3)}$; and $V_{PFC(Ni)(c)} = V_{c+(9)}$ or $V_{c-(9)}$.

V. SIMULATION RESULTS AND DISCUSSION

A two-bus 110 kV transmission line is used to illustrate the effectiveness of the proposed PSPFC. Fig. 10 shows a PSPFC embedded to a two bus transmission line. The study investigated power flow control limits of the considered PSPFC, control preciseness, and active and reactive power flow control independence.

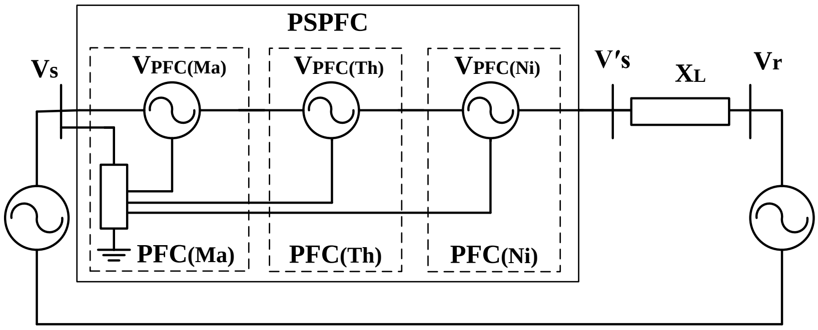

Fig. 10. A PSPFC connected to a two bus transmission line

100 MVA and 63.509 kV are taken as power and voltage base, respectively. $V_R = 1.0\ pu$. The natural transmission angle is $\delta = 15^{\circ}$; and line and series PSPFC's reactance are $X_L = 0.25\ pu$. Based on Section 4, voltage ratings of PFC_{Ma}, PFC_{Th}, and PFC_{Ni} windings are 25.404 kV, 2.12 kV and 0.706 kV respectively. Results are obtained analytically and through simulation in MATLAB/SIMULINK. Natural (i. e. non-controlled) flows of transmission line are 1.035 pu real power and 0.1363 pu capacitive reactive power at the receiving end.

A) Power Flow Control Limits of the PSPFC

Broadest values of voltage magnitude and phase angles of the PFC_{Ma}, PFC_{Th}, and PFC_{Ni} are activated for the purpose of determination of active and reactive power flow control limits of the PSPFC. Tables 1 and 2 show these limits of real and reactive power flow control. Results are obtained through simulation in environment of MATLAB/SIMULINK, and calculation using (4) and (5).

TABLE 1
REAL POWER-PHASE ANGLE LIMITS OF PSPFC AND CONVENTIONAL PST

Phase Angle Shift Limits, °				**Real Power Flow Control Limits, pu**			
PSPFC		PST		PSPFC		PST	
23.97	- 23.97	21.81	-21.81	2.753	- 0.682	2.581	- 0.511
Real Power Controllability				± 1.718		± 1.546	

TABLE 2
REACTIVE POWER-VOLTAGE LIMITS OF PSPFC AND CONVENTIONAL VRT

Voltage Magnitude Control Limits, pu				**Reactive Power Flow Control Limits, pu**			
PSPFC		VRT		PSPFC		VRT	
1.257	0.743	1.231	0.769	0.855	- 1.129	0.756	- 1.029
Reactive Power Controllability				± 0.992		± 0.893	

B) Preciseness of Control Action of the PSPFC

Figs. 11 and 12 show actions of PSPFC on real power and phase-angle, and reactive power and voltage magnitude respectively. The figures reveal the preciseness of action of the PSPFC as compared to that of PST and VRT. This preciseness results in flexibility on phase shifting and voltage regulating of PSPFC as compared to that of conventional PST, and conventional VRT respectively.

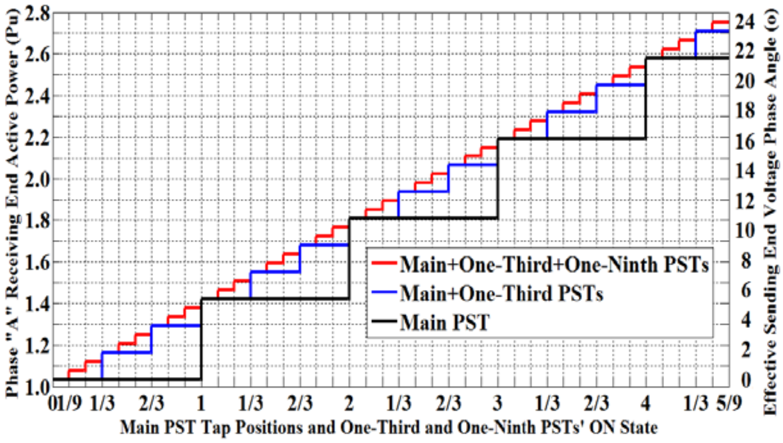

Fig. 11. Receiving end active power flow and effective sending end voltage phase angle considering quadrature leading voltage

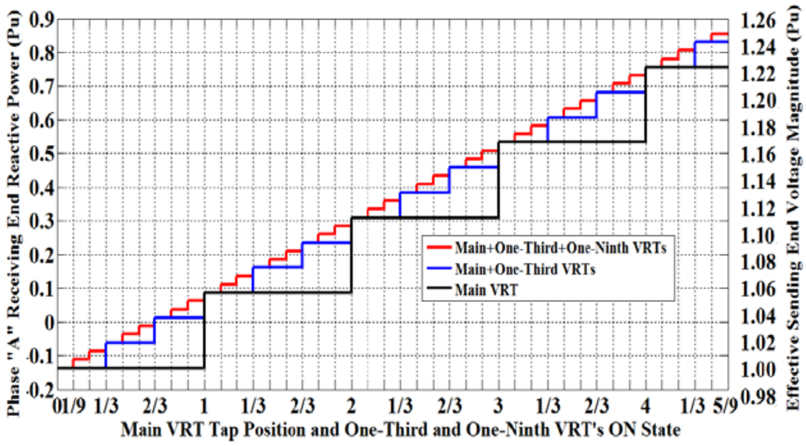

Fig. 12. Receiving end reactive power flow and effective sending end voltage magnitude considering the direct increasing voltage

C) Independent Active and Reactive Power Flow Control Capability of the PSPFC

The desired independent active and reactive power flow control requires selecting appropriate pairs of voltage magnitude and phase angle. Algorithm of switching of PFC_{Ma}, PFC_{Th} and PFC_{Ni} for implementation of independent active and reactive power flow control is presented here. Appropriate windings of PFC_{Ma}, PFC_{Th} and PFC_{Ni} are activated to realize each desired operating state. Two control strategies are implemented for that purpose. The first is to maintain active power flow and control reactive power flow as can be seen in sections 2, 3 and 4. The second is to maintain reactive power flow and control active power flow as can be seen in sections 6 to 10. No part of PSPFC is activated in sections 1 and 5. In case the desired compensation voltage is not achievable exactly, the possible operating point that results in least control-error is selected. However, owing to the fractional voltage that the PSPFC provides, control-error is very small in case that it exists. Operating points of PSPFC, along line *a-b* in Fig. 13, result in variable active power with a constant reactive power. On the other hand, operating points of PSPFC, along line *c-d* in Fig. 14, result in variable reactive power with a constant active power.

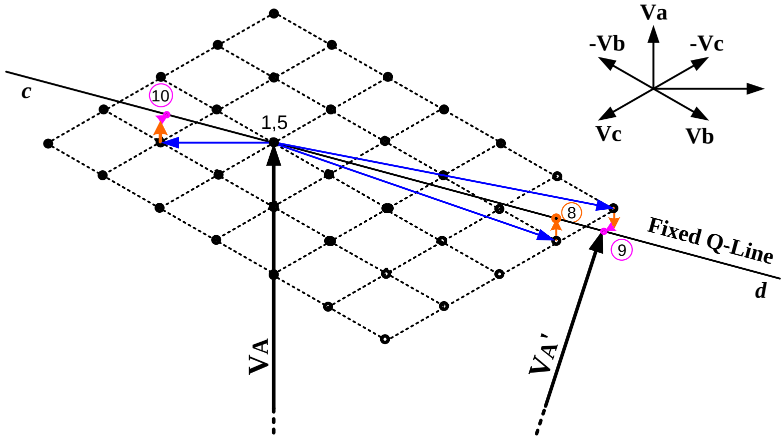

Fig. 13. Operating points of PSPFC that realizes variable active power and constant reactive power

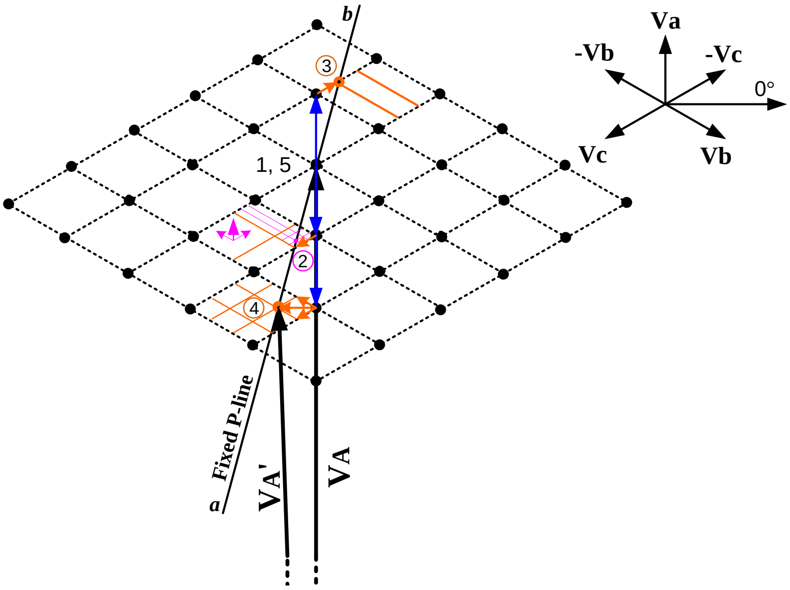

Fig. 14. Operating points of PSPFC that realizes variable reactive power and constant active power

Fig. 15 depicts results of controlling the active power while maintaining reactive power fixed; and controlling the reactive power while maintain active power fixed. Table 3 shows activated windings in each section. Tap position of each winding of PFC_{Ma} is shown. Activated windings of PFC_{Th} and PFC_{Ni} are given symbol (▲). All non-activated windings are given symbol (-).

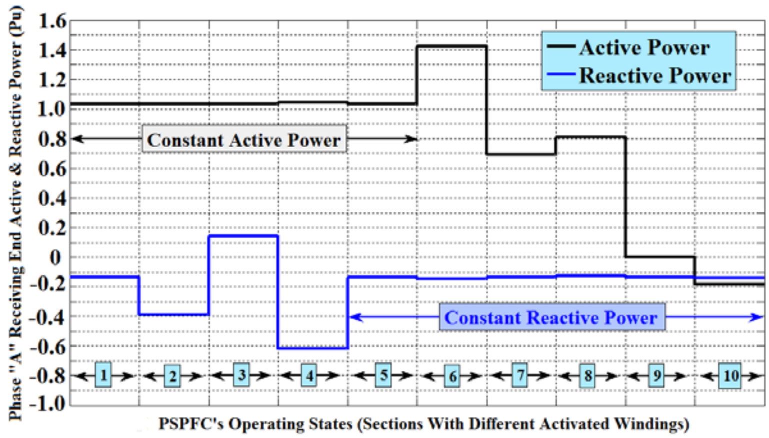

Fig. 15. Independent real and reactive power flow control

TABLE 3
ACTIVATED WINDINGS OF EACH PFC THAT REALIZE INDEPENDENT REAL AND REACTIVE POWER FLOW CONTROL OF FIG. 15

Section	Operation	Main PFC				One-Third PFC				One-Ninth PFC			
		V_b	V_c	$-V_b$	$-V_c$	V_b	V_c	$-V_b$	$-V_c$	V_b	V_c	$-V_b$	$-V_c$
1,5	Natural (Non-Controlled = No PFC Winding is Activated)												
2	Fixed P	0.1	0.1	-	-	-	▲	-	-	-	-	▲	▲
3		-	-	0.1	0.1	-	-	-	▲	-	-	-	-
4		0.2	0.2	-	-	-	▲	▲	-	-	-	-	-
6	Fixed Q	0.1	-	-	-	-	-	▲	▲	▲	-	-	-
7		0.1	-	-	-	▲	-	-	▲	-	-	▲	▲
8		0.4	-	-	0.1	-	-	-	-	-	-	▲	▲
9		0.4	-	-	0.2	▲	▲	-	-	-	▲	-	-
10		-	0.1	0.1	-	-	-	▲	▲	-	-	-	▲

Figs 16 and 17 show sending and effective sending end three phase voltages that respectively correspond to sections 4 and 9 of independent active and reactive power flow control in Fig. 15. To maintain active power flow and transfer more capacitive reactive power, the voltage injected by PSPFC caused a noticeable reduction in voltage magnitude and a slight phase angle advance at sending end as can be seen in Fig. 16. On the other hand, to maintain reactive power flow and decrease active power flow to almost zero, the voltage injected by PSPFC caused a slight voltage magnitude reduction and a noticeable phase angle retard at sending end as shown in Fig. 17.

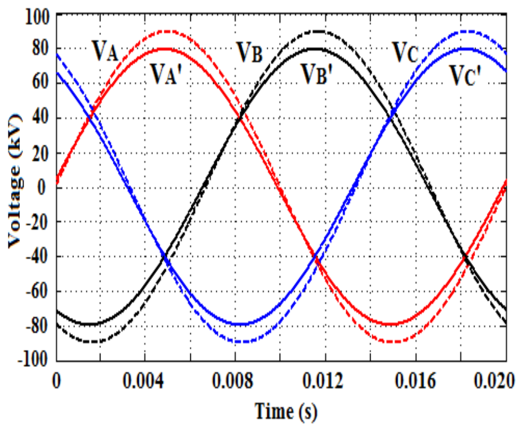

Fig. 16. Voltages of sending end and effective sending end for case of section 4

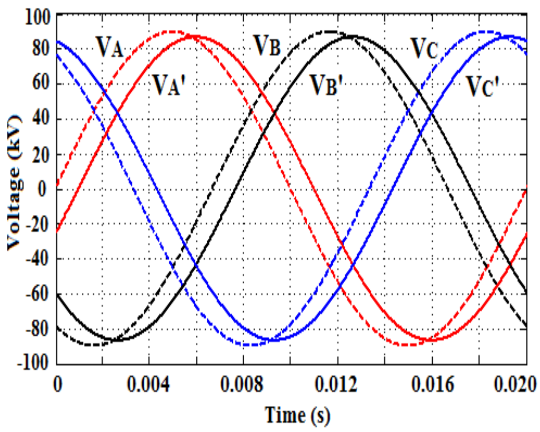

Fig. 17. Voltages of sending end and effective sending end for case of section 9

From Fig. 11, the considered conventional PST has a phase shifting step of 5.711º, and a real power step of 38.7 MW. However, the proposed PSPFC has a phase shifting step of only 0.6366º, and a real power step of only 4.3 MW. As well, from Fig. 12, the considered conventional VRT has a voltage step of 3.683 kV, and a reactive power step of 22.31 MVar. Conversely, the proposed PSPFC has a voltage step of only 0.381 kV, and a reactive power step of only 2.48 MVar. One can notice that step size of PSPFC is 1/9 that of conventional PST and VRT for active and reactive power flow control respectively. These results reveal that with fractionally rated windings and thyristor switches, PSPFC realizes precise-steps based active and reactive PFC. Thus, PSPFC assures highly reduced control-error as compared to conventional PST and VRT. It accordingly provides increased flexibility. Additionally, owing to the use of thyristor switches, PSPFC has an improved response rate. As well, it is evident from Tables 1 and 2 that the device achieves wider real and reactive power control limits. As expected, compared to PST and VRT, PSPFC results in broader control limits. It increases (decreases) voltage magnitude to a greater (lesser) degree than VRT does; and advances (retards) voltage phase angle to a greater (lesser) degree than PST does.

VI. CONCLUSIONS

Deficiencies of conventional PST, VRT, and ST are large steps, limited operating points, and relatively slow response. These devices do not always ensure optimal control action owing to the control-error that they experience. While increasing the number of OLTCs can reduce drawbacks of PST, VRT, and, ST, response rate will be still slow. A precise steps based power flow controller (PSPFC) that possesses most advantages of existing power flow controllers (PFCs) is presented in this paper. PSPFC is a phase shifting and voltage regulating transformer in a single unit. As compared to conventional PST, configuration of PSPFC is modified; and fractional compensation windings and thyristor switches are added, which are rated to only 0.019245 and 0.006415 pu voltage. Thyristor switches ensure fast response of PSPFC. PSPFC has more chances of error-free control; and when error exists, PSPFC has less control-error. It is more flexible, has fast response, and has an extended power flow control range. Additionally, it has highly independent active and reactive power flow controllability. Owing to its advantageous operational characteristics, the device is useful for grid flexibility enrichment, loadability enhancement, and security and stability maintenance.

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