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Power transistor-assisted Sen Transformer: a novel approach to power flow control

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ABSTRACT

The importance of flexible power flow control in electric power transmission networks is increasing owing to many factors that have arisen. Sen Transformer (ST) is one of the attractive power flow controllers. It has a wide control range, independent active and reactive power flow control capability, and is economically attractive. However, it operates in stepwise mode, has limited operating points, relatively slow response rate, and suffers from compensation error. Motivated by the limitations of the ST, power transistor assisted ST (TAST) as a novel power flow controller is proposed in this paper. The TAST consists of a highly-rated ST and a lowly-rated AC chopper based transistorized ST (TST). This paper first points to the importance of transmission lines' power flow control and reviews available power flow control devices. It then introduces the proposed TAST, determines the ratings of the TST and the switching pattern of its choppers. Next, it demonstrates the steady-state performance of the TAST, determines its control limits, compares the TAST to the ST and the unified power flow controller (UPFC), and the different control strategies of the TAST. In this paper, the TAST is modeled in MATLAB/SIMULINK and tested in an equivalent two bus system and in the IEEE-14 bus test system. The work also demonstrates improvement of the response rate of the ST. Cost analysis of the TAST is also done and is compared to that of the equivalent UPFC.

Based on the results, the TAST realizes continuous, error-free, more flexible operation, improved response rate, and low cost. Moreover, the TAST provides 14.62% wider power flow control range. In conclusion, the TAST's operational characteristics are closely comparable to that of the UPFC with the advantage of lower cost and extended control area.

1. Introduction

Deregulation of the electric power sector has opened the door for investment in power generation. The environmental concerns and the search for alternatives to fossil fuel have encouraged integration of wind and solar energy, and electric vehicles (EVs). These factors have increased the power grid's dynamics. Wind and solar are intermittent in nature, and the EVs have charging-discharging and connection-disconnection operation cycles. On the other hand, the unwillingness of new lines' installation, the steady increase in demand and thus in generation, and the natural flow of power, have created congestion of some transmission lines while some other ones are lightly loaded. These factors and the increased interconnection of grids and the frequent power system components outage have necessitated transmission lines' power flow control and enhancement of network flexibility. In the current circumstances, the dynamic adaptation of the grid through its controls to meet the arising dynamics successfully is highly essential. This addaptation can relieve the congestion, augment the loadability, optimize the operation, and enhance the power systems' stability and security. Integration of power flow control (PFC) devices presents the desired flexibility and also delays or even cancels the need for new lines' installation.

The flexible AC transmission systems (FACTS) devices are highly efficient PFC devices [1–4]. The shunt FACTS devices, the static var compensator (SVC) and the static synchronous compensator (STATCOM) [5,6] are suitable for voltage control. The SVC can behave as an inductive reactance that absorbs reactive power, or a capacitive

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reactance that provides reactive power [5,6]. However, the reactive power that the SVC absorbs or generates highly depends on the bus voltage. When the bus voltage is low, which is the time when the capacitive reactive power is most needed, the SVC fails to provide a sufficient amount of the capacitive reactive power. The STATCOM is an inverter-based reactive power compensator. The current through a STATCOM is almost in quadrature with the line voltage; therefore, a STATCOM emulates an inductive or a capacitive reactance. The main function of a STATCOM is to control the reactive current that flows through it. The STATCOM's operation is not affected when the bus voltage drops, and thus, it is more effective than the SVC. On the other hand, the series FACTS devices, the thyristor controlled series capacitor (TCSC) and the static synchronous series compensator (SSSC) [5,6] are suitable for transmission lines' reactance control. The thyristor controlled phase shifter (TCPS) [6,7] as a shunt-series device is suitable for phase-angle and active power flow control. However, these devices are unable to control the active and reactive power flow independently, which is necessary for the most efficient transmission of power. The most versatile PFC device is the unified power flow controller (UPFC) [5]. It can simultaneously or selectively control voltage magnitude, phase angle, and line reactance, and thus it can provide independent active and reactive power flow control [5]. However, the high cost of the UPFC limits its broad usage [8]. Up to date, there are only three UPFC practical installations [9–11]. The DC energy storage element implemented in the voltage source converter (VSC) devices is a primary factor contributing to size and cost. It is an expensive part that most often damages [12] and shortens the converter's lifetime [13]. Converters without DC-link are seen as a future concept for specific applications [13]. On the other hand, the non-power electronic based FACTS devices include on-load tap-changing (OLTC) based transformers such as voltage regulating transformers (VRT) and phase shifting transformers (PST) [14]. Sen transformer (ST) [14–16] is relatively a newer attractive PFC device that combines a VRT and a PST in one unit. The ST is a three-phase transformer with multiple secondary side windings. Its primary side's three-phase windings are connected in Y, and called the exciter, and its secondary side consists of three groups of windings, with three phase windings in each group, and called the compensator [14]. Each of these groups is dedicated to compensate one phase of the transmission line. Windings of each group of the compensator part have a number of tap points. These windings are connected in series to each other, and their resulting voltage is injected in series to the transmission line to be compensated. ST uses transformer and OLTCs and can function similar to a VRT and a PST simultaneously or selectively. When the ST injects a compensating voltage in series to a transmission line, it modifies the line voltage to a specific magnitude and phase angle that realizes the transmission grid's desired operation. ST's operational characteristics are comparable to those of the UPFC [8,14,17] with some pros and cons. ST can independently control the active and reactive power flow. As compared to the UPFC, advantages of the ST include its less power loss, power system's frequency operation, and its economical attractiveness as its cost is in the range of 20% of the equivalent UPFC [8,14]. However, similar to the other OLTC based devices, ST operates in step-wise mode due to the discrete nature of the taps [16]. It is thus less flexible as it has limited operating points since only a few tap points are available. Consequently, the ST suffers from occurrence of compensation-error as it is not always able to inject the exact desired compensation voltage. The compensation-error diminishes only in a few individual cases when the desired compensation voltage exactly meets one of the possible operating points of ST. In most cases, among four possible compensation voltages, in order to select the tap-position that realizes the minimum error, Faruque and Dinavahi [18] presented a tap selection algorithm. Furthermore, ST's response rate may not be sufficient to successfully meet the arising dynamics in power transmission systems. The limitations of ST do not guarantee the highest desired flexibility. With its advantages retained, ST's operational characteristics can be enhanced further. Based on the above review, a unified power flow controller that combines most advantages of both power electronics and non-power electronics-based FACTS devices would be highly attractive.

Considerable research efforts are being exerted to develop suitable alternative devices for power flow control. Many PFC devices with fractionally rated converters are presented in [19,20]. Among them, the controllable network transformer (CNT) [19] combines an OLTC transformer with a fractionally-rated AC-AC converter, as a cost-effective device for dynamic power flow control at medium voltage levels. There are some strategies to scale the CNT to transmission voltage levels [21]. Very recently, Chen et al. [22] presented a decoupled closed-loop controller to facilitate the CNT with the active-reactive power flow control selectivity. On the other hand, Yuan et al. [23] introduced an improved ST (IST), which consists of high-capacity ST and low-capacity UPFC. However, as compared to the PQ plane's shape of the UPFC and that of the ST, the PQ plane's shape of the CNT is not circular. While the significance of a power flow controller is mainly in its active power flow control capability, the active power flow control limit of a CNT is typically half of the reactive power flow control limit.

It is attractive to combine the wide-range PFC of the ST to the fractionally rated converters. The characteristics of ST can be enhanced at the expense of the fractionally rated converters. The objective of this work is to facilitate the ST with continuous, more flexible, and error-free operational characteristics through usage of power electronic (PE) switches. These PE switches can also improve the response rate of the ST [15]. While the response rate of the ST is reasonable for most utility applications [8], fast acting PFC devices enable safe operation of the grid with reduced stability margins, and thereby allow approaching lines' thermal limits [24]. Replacing the mechanical taps of the ST in its available configuration, by PE switches, may not be cost effective. High voltage and/or current rated PE switches would be needed, and based on the circuit topology, the modified PFC device may still operate in step-wise mode with limited operating points, or high harmonic distortion would be created. It is critical to select the appropriate location of the PE switches within a PFC device to ensure fulfilling the desired technical characteristics with reasonable overall cost. Introducing fractionally rated converters is advantageous and can accomplish the desirable technical and economic features. In light of this, a novel approach of power transistor assisted ST (TAST), which consists of a high rated ST and a fractionally rated AC-chopper based transistorized ST (TST) is presented in this paper. Since the TST is fractionally rated, the PE switches and the other circuit components are fractionally rated, and consequently, added cost to the already available ST is small. In this paper, the simulation results revealed that the TAST is an encouraging new PFC device. The proposed TAST can improve utilization of the transmission lines, enhance the loadability, relieve congestion of the overloaded lines and thus reduce the power system's stress. It can maintain the power system's security during components' outage, and enhance the stability during disturbances. TAST can aid continuous adaptation of the grid to meet the arising dynamics successfully, optimize the grid operation, and help in successfully hosting wind and solar energy units, and the forthcoming electric vehicles (EVs). The manuscript is organized as follows: Section 2 describes the TAST; Section 3 presents selection of the AC voltage regulator that would be augmented on ST and the AC-chopper's gating signals' pattern. Section 4 introduces determination of the ratings of the TST windings, and Section 5 presents TAST's operation principle. TAST's cost is analyzed and compared to that of an equivalent UPFC in Section 6. The TAST and ST action and their operating