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4-Node Test Feeder with Step Voltage Regulators ☆

Cristina González-Morán *, Pablo Arboleya, Rejwan R. Mojumdar, Bassam Mohamed

Department of Electrical Engineering, University of Oviedo, Spain

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ABSTRACT

This work has two main contributions; First, the development of a general, exact and standardized Step Voltage Regulator model considering all possible configurations and second, the proposal of a 4-Node Test System for testing and evaluation of three-phase Step Voltage Regulator connections. Although the 4-Node Test Feeder for testing three phase transformer configurations is already available in the literature, there is not such model for the inclusion, testing and validation of Step Voltage Regulators in a test feeder. With the work presented in this paper, a new test system will be available to evaluate and benchmark programs or algorithms that attempt to include different configurations of Step Voltage Regulators. The formulation is stated for all three phase Step Voltage Regulators; i.e. wye, close-delta and open-delta connections, both type A and B regulators, in raise or lower positions. Then, all these models are included in a 4-Node Test Feeder to obtain several power flow solutions. All obtained results will be available for power flow software developers on-line.

1. Introduction

Step Voltage Regulators (SVRs) have been employed in power feeders for many decades [1–4]. Its modeling posses particular importance in power flow studies of unbalanced distribution networks [5–7] and is gaining even more importance in distribution feeders with the proliferation of Distributed Generation (DG) [8]; several voltage control possibilities can be achieved by coordinating the small generators and storage units installed near customers and the well-known switched capacitors and step voltage regulators [9]. As an example, the authors in [10] proposed a coordinated control of energy storage systems with SVRs to mitigate the voltage rise caused for high penetration levels of photovoltaic systems. Similar applications can be found in [11] or [12]; In both works the combination of SVRs, Static VAR Compensators (SVC) and Shunt Capacitors (SC) are applied to achieve voltage control in distribution feeders including DG. In [13] the control schedules of SVRs are updated according to wind power predictions to compensate voltage variations derived form high penetration of wind power plants. Many other works related to coordination of SVRs in distributed systems with DG can be found in the literature [14–17]. In [14] a voltage estimation is used to control over-voltages in residential networks with varying PV penetrations. In [15] the authors coordinate the location of reactive power injections from the PV inverters with transformer tap positions in a distributed system as a way to constrain voltage variations. In [16] an unbalanced power flow is used to obtain the influence of SVRs and DGs penetrations in power losses and voltage profiles. In [17] several voltage control techniques; On Load Tap Changers (OLTC), SVR, SC, Shunt Reactor (ShR), and SVC are optimally controlled in coordination with DG.

In [18] a robust, low-cost and high-efficiency voltage regulator is designed for rural networks with serial voltage compensation. In [19] the authors propose distributed voltage control for multiple voltage regulation devices; on-load tap changers, step voltage regulators and switched capacitors in the presence of PV. They tested the scheme in a medium voltage feeder in California. In [20] detailed models for open-delta connected SVR are presented. The authors developed a bus admittance model suitable for unbalanced power flow studies.

Regarding the optimization of tap positions, in [21] an algorithm to set the positions of regulating transformers is proposed. The algorithm is valid for unbalanced and distributed systems. In [22], the authors propose a linear power flow formulation to optimally configure a distribution system using, among other control variables, the tap positions in voltage regulators. In [23], also the tap positions of transformers are included as optimization variables.

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* Corresponding author.
E-mail address: gonzalezmorcristina@uniovi.es (C. González-Morán).
URLs: http://cristina.dieecs.com/contact (C. González-Morán), http://arboleya.dieecs.com (P. Arboleya).

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Directly related to SVR modeling, we can find the work in [24], in which there is a brief description of a SVR model to be included in an unbalanced power flow formulation based on the current injection method. In [25] the authors are capable of designing dynamic SVRs, but they considered a single phase model. From their point of view, this model can be used into a 3 phase system taking into account that each phase works separately, so they do not considered closed delta or open delta configurations. In [26,27] Kersting addressed the modeling of some SVR configurations to study some of their applications. Those works cover the distribution system modeling in *abc* reference frame, the SVR control mechanism by estimating *R* and *X* line settings and other applications of SVRs in distribution systems.

Looking at this literature review we can conclude that SVR modeling and testing are of great importance for distribution systems and power flow studies, and are expected to be even more present with the proliferation of DG. However, we have found that, although there are many extensive works dealing with SVR inclusion in power flow studies, there is not any work presenting general models and results for all possible configurations. This work might be also used as a benchmark for other researchers.

Reviewing the IEEE test feeders [28] of the IEEE PES Distribution System Analysis Subcommittee's Distribution Test Feeder Working Group, we will find a set of common data for testing and validation of Distribution System Analysis software. More specifically, the 4-Node Test Feeder offers a set of comparison results to deal with transformers of various configurations [29].

In this paper, the IEEE 4-Node Test System in [28] will be modified; The transformer is removed to introduce SVRs instead. We propose the general model for SVR and the 4-Node Test Feeder with SVR, both of them will be available for designers and power flow developers as a test system with detailed SVR modeling and results.

The paper is structured as follows: First, a general matrix formulation will be stated for all possible configurations: 2 grounded-wye connections (type A and B regulators), 2 close-delta connections (type A and B) and 6 open-delta connections depending on the selection of phases (3 cases for type A and 3 other cases for type B). The regulators can be at raise or at lower positions. All these SVR configurations defined a 4-Node Test Feeder that has been formulated in $\alpha\beta0$ frame, following the procedure of [30], but adapted for SVRs. Then, the power flow formulation is presented for balanced and unbalanced loading at different tap positions. Finally, the problem is solved with the Backward Forward Sweep (BFS) algorithm of [31] to obtain the results for all possible configurations. Due to the high extension of results that were obtained, only some examples are included in this paper. The rest of results will be available on line (see Supplementary material).

2. SVR modeling

2.1. Single phase Step Voltage Regulator

A model for an ideal single phase regulator can be derived from [27]. If the series impedance is to be also considered, then, that ideal model needs to be modified: In Fig. 1 the single phase configurations are displayed. *P* stands for primary (or source side) and *S* stands for secondary (load side). For the sake of simplicity, as it will be justified later, the series impedance is concentrated at the secondary side for type A configurations and at the primary side for type B configurations. The relationships between voltages and currents for the ideal SVR are summarized in Table 1, where N_1 and N_2 are the number of turns of the shunt and series windings respectively. a_R is the effective turns ratio and is defined in a different way depending on the type of regulator, as it is shown in the table. From Fig. 1 it can be deducted that P = P′ for type A and S = S′ for type B regulators.

The relationship between primary and secondary voltages for type A, single phase regulators can then be written as follows:

$$V_{P'} = V_{S'}\frac{1}{a_R} \tag{1}$$

$$V_{P'} = V_P \tag{2}$$

$$V_{S'} = V_S + ZI_S \tag{3}$$

replacing (2) and (3) into (1) and taking V_P apart, it is obtained:

$$V_P = \frac{1}{a_R}V_S + \frac{1}{a_R}ZI_S \tag{4}$$

For type A regulators, the primary and secondary currents can be related by:

$$I_P = a_R I_S \tag{5}$$

The corresponding equations for type B, single phase regulators, with impedance on the primary side are stated as:

$$V_{P'} = V_{S'}\, a_R \tag{6}$$

$$V_{S'} = V_S \tag{7}$$

$$V_P = ZI_P + V_{P'} \tag{8}$$

replacing (6) and (7) into (8) it is deducted that:

$$V_P = a_R V_S + ZI_P \tag{9}$$

And finally, primary and secondary currents for type B regulators can be related in:

$$I_P = \frac{1}{a_R}I_S \tag{10}$$

Single phase Eqs. (4), (5) for type A regulators and (9), (10) for type B regulators are the baseline for the definition of the three phase configurations.

2.2. Three phase connections

Three phase configurations to be considered are wye, close delta and open delta. In following subsections, upper cases letters will be used for primary (or source) side and lower case letters will represent secondary (or load) side. In the present work, type A regulators have been chosen for three phase connections. However, the same procedure can be extended to type B regulators. For the power flow calculations, the mathematical model in [30] and a BFS algorithm are going to be used. The formulation is valid for any transformer connection, and the algorithm in $\alpha\beta0$ frame solves the problems of some transformer connections including three wire configurations (Δ and ungrounded wye) in *abc* frame; especially $Y_g\Delta$ connection. The problems are solved by means of the zero components of voltages and currents that in $\alpha\beta0$ frame are always available [30].

There are three general equations that represent all three phase connections:

$$[\mathbf{V}]^{\mathrm{P}}_{\alpha\beta0} = \mathbf{N}_{\mathbf{II}_{\alpha\beta0}}[\mathbf{V}]^{\mathrm{S}}_{\alpha\beta0} + Z\mathbf{N}_{\mathbf{I}_{\alpha\beta0}}[\mathbf{I}]^{\mathrm{PS}}_{\alpha\beta0} \tag{11}$$

$$[0] = -[\mathbf{I}]^{\mathrm{P}}_{\alpha\beta0} + \mathbf{N}_{\mathbf{IV}_{\alpha\beta0}}[\mathbf{I}]^{\mathrm{PS}}_{\alpha\beta0} \tag{12}$$

$$[0] = [\mathbf{I}]^{\mathrm{S}}_{\alpha\beta0} + \mathbf{N}_{\mathbf{III}_{\alpha\beta0}}[\mathbf{I}]^{\mathrm{PS}}_{\alpha\beta0} \tag{13}$$

The sub-index $\alpha\beta0$ are used in the expressions because all the elements in brackets are three phase $\alpha\beta0$ components (voltages or currents). The super-indexes P and S stand for primary and secondary respectively. The super-index PS stands for primary or secondary, depending on the transformer connection. Eqs. (11)–(13)