Mixed Model-Free Adaptive Controller with Virtual Reference Feedback Tuning Applied to Secondary Voltage Control ⋆

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Abstract: This paper shows the design of data-driven secondary voltage control (SVC) using synchrophasor measurements to eliminate voltage violations in electric power systems. A closed-loop strategy is carried out with the participation of the available generators, to increase the utilization of their reactive power capability and decrease the need for additional reactive power sources. A Model-Free Adaptive Control (MFAC) algorithm is used to perform the closed-loop control, and their initial parameters are tuned by the Virtual Reference Feedback Tuning (VRFT) approach using only I/O data (without any system model information). The proposed MFAC-VRFT-SVC strategy was applied to the benchmark IEEE 39 bus system, which was modeled using MATLAB/Simulink software, and robust performance was achieved under disturbances.

Keywords: Data-Driven Control, Model-Free Adaptive Control, Secondary Voltage Control, Virtual Reference Feedback Tuning.

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1. INTRODUÇÃO

In recent years, power systems around the world have been experiencing significant changes, resulting of the massive integration of renewable generation and the difficulty to build new transmission lines due to environmental constraints. In a recent review (H. Sun et al., 2019), the authors discussed the effect of these changes on voltage control. The authors clearly stated the necessity of new voltage control methods and schemes to cope with new challenges. Some of the key technologies to improve voltage control performance are the Wide Area Measurement Systems (WAMS) and the hierarchical control schemes. The hierarchical voltage control scheme is divided into primary voltage control (PVC), secondary voltage control (SVC), and tertiary voltage control (TVC) (Voropai et al., 2023). In this paper, the main goal is to improve the performance of the secondary level, which is responsible for maintaining the voltage profile at an acceptable level across the entire power grid.

The SVC consists of a feedback control loop that regulates transmission-side voltage at some selected pilot buses. Practically, this is accomplished by adjusting individual generator Automatic Voltage Regulators (AVR) set-points, static or synchronous condensers, and transformer taps, etc. It should be noted that pilot bus voltage must represent the voltage in its neighborhood. Traditionally, the SVC is designed off-line using high-order linear or nonlinear models (Voropai et al., 2023; Kruse et al., 2022). Obviously, the performance of the resulting SVC controller is directly dependent on the accuracy of the obtained model. Detailed representation of these models with all associated controllers may take significant effort and require using models with a substantial number of states. Depending on the level of detail of the models and the size of the system, these models may not accurately represent all the system dynamics and their control interactions. Therefore, the performance of these model-based methods can be impaired in power systems with massing penetration of renewable generation.

In this context, data-driven control methods represent a potential solution, because some problems that arise from model-based methods, such as unmodeled dynamics and the difficulty of obtaining accurate power systems models, are avoided. In the literature, some data-driven methods, like Virtual Reference Feedback Tuning (VRFT) and Model Free Adaptive Control (MFAC), are available (Precup et al., 2021). In the MFAC algorithm, a pseudo-partial derivative is estimated online by using I/O data according to some weighting factors (Hou and Xiong, 2019). These weighting factors are important adjustable parameters for system stability and performance. However, there are no guidelines for an appropriate selection of these parameters. On the other hand, the VRFT algorithm is a method which directly finds the controller's parameters without any weighting factors (Remes et al., 2021). In the literature, both methods have been applied to several

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power system problems. In Zhao and Lu (2018), the authors used the MFAC algorithm in an SVC problem, but the initialization of weighting factors was not addressed. In Nascimento et al. (2020), the authors applied the VRFT algorithm to the SVC problem in order to eliminate voltage violations in electrical power systems. Likewise, in Bernado et al. (2020) the authors present a modified version of VRFT to re-tune the control loops of the power system stabilizers (PSS) in order to improve the oscillations damping. In this work, a SVC design based on the on-line MFAC method is proposed. The weighting factors and the initial adaptive parameter of the MFAC controllers are set by using the off-line VRFT method.

The rest of the paper is organized as follows: The concepts of the MFAC method are presented in Section 2. Section 3 presents the VRFT idea. Section 4 presents the multilevel SVC control scheme. Section 5 presents the methodology proposed. Section 6 presents the simulations and results obtained. Finally, concluding remarks are given in Section 7.

2. PRINCIPLE OF MODEL-FREE ADAPTIVE CONTROL

Consider a class of nonlinear discrete-time systems described by

$$y(k+1) = f[U_k^{k-n}, u(k), Y_{k-1}^{k-m}, k+1] \tag{1}$$

where $u(k) \in R$ and $y(k) \in R$ are the control input and the system output at time instant k, respectively, n and m are unknown orders of input and output respectively, $f(.)$ is a general nonlinear function, Y_{k-1}^{k-m} is $y(k), \ldots, y(k-m)$, U_k^{k-n} is $u(k), \ldots, u(k-n)$, and R is a real number set.

The system in (1) needs to meet the following assumptions: (A1) It is generalized Lipschitz, that is to say, $\Delta y(k+1) \leq b\Delta u(k)$, is reasonable for any k and $\Delta u(k) \neq 0$. Where $\Delta y(k+1) = y(k+1) - y(k)$, $\Delta u(k) = u(k) - u(k-1)$, and b is a constant; (A2) Regarding to control input $u(k)$, the partial derivative of $f(.)$ is considered as smooth; and (A3) It is observable and controllable.

Considering the nonlinear system (1) and the proposed (A1) and (A2), there exists a time-varying parameter as Pseudo Partial Derivative (PPD) $\varphi(k)$ at each time interval. The PPD is a derivative value of the nonlinear function $f(.)$ between $u(k-1)$ and $u(k)$ at a certain sample time. Using PPD, a Compact Form Dynamically Linearization (CFDL) model can be written as $\Delta y(k+1) = \varphi(k)\Delta u(k)$, where $|\varphi(k)| \leq b$ is bounded for any time interval k, $\varphi(k)$ are time-varying parameters, and $\Delta y(k) = y(k) - y(k-1)$. The control law of MFAC is given as follows by minimizing the control criterion

$$J(u(k)) = |y^*(k+1) - y(k+1)|^2 + \lambda|u(k) - u(k-1)|^2 \tag{2}$$

where $y^*(k+1)$ is the desired output and λ is the penalty weighted factor.

If the case $\Delta u(k) = 0$ comes forth at certain sampling time, equation (1) can be transformed into Compact Form Dynamic Linearization (CFDL) model as $y(k+1) - y(k-\sigma+1) = \varphi(k)[u(k) - u(k-\sigma)]$ and

$$y(k+1) = y(k) + \varphi(k)\Delta u(k) \tag{3}$$

By substituting equation (3) to equation (2) and solving $\frac{\partial J(u(k))}{\partial u(k)} = 0$, the control law $u(k)$ is obtained as follows

$$u(k) = u(k-1) + \frac{\rho\hat{\varphi}(k)}{\lambda + ||\hat{\varphi}(k)||^2}[y^*(k+1) - y(k)] \tag{4}$$

where ρ is the step factor.

In the control law defined by (4), the only unclear parameter is the characteristic parameters $\varphi(k)$, so the main task is to find it. Consider the estimation criterion function as $J(\varphi(k)) = |y^*(k+1) - y(k+1) - \varphi(k)\Delta u(k)|^2 + \mu|\varphi(k) - \hat{\varphi}(k-1)|^2$, can be estimated as given by:

$$\begin{aligned}\hat{\varphi}(k) &= \hat{\varphi}(k-1) \\ &+ \frac{\eta\Delta u(k-1)}{\mu + ||\Delta u(k-1)||^2}[\Delta y(k) - \hat{\varphi}(k-1)\Delta u(k-1)]\end{aligned} \tag{5}$$

$$\hat{\varphi}(k) = \hat{\varphi}(1) \quad \text{if} \quad |\hat{\varphi}(k)| \leq \varepsilon \quad \text{or} \quad |\Delta u(k-1)| \leq \varepsilon \tag{6}$$

where $\lambda > 0$, $\mu > 0$, $\rho \in (0, 1]$, $\eta \in (0, 2]$, and ε is a small positive constant.

3. THE VIRTUAL REFERENCE FEEDBACK TUNING IDEA

In this section, an overview of the VRFT method is presented. This method was first introduced in Guardabassi and Savaresi (2000). The VRFT is a direct data-driven method, which means that it is capable of directly estimating the controller parameters from a plant using only I/O data. This is an off-line design approach with a low computational burden for the control synthesis (one-shot method).

To understand the basic idea of the method, consider a feedback control system illustrated in Figure 1. This physical system is composed of a process $G(z)$ and a controller $C(z;\theta)$. The transfer function $M(z)$ is defined as the reference model used by the designer to define closed-loop dynamic performance. With the control objectives specified in $M(z)$, the main goal is to estimate the value of θ (vector of parameters of the controller) for the physical plant.

To estimate the controller parameter (θ), the authors in Campi et al. (2002) proposed using the concept of *virtual reference* ($\tilde{r}(k)$). This concept consists in impose that the closed-loop system has the same transfer function as the reference model. As a result, the output of the two systems should be the same for a common $\tilde{r}(k)$. Figure 1 shows the two systems with the same *virtual reference* and output ($y(t)$). Assuming that the process model is unavailable, a set of N input-output samples $\{u(k), y(k)\}_{k=1:N}$ can be obtained from an open-loop experiment. With the reference model $M(z)$ and the output signal $y(k)$ available, the *virtual reference* signal $\tilde{r}(k)$ can be obtained using:

$$\tilde{r}(k) = [M(z)]^{-1}y(k) \tag{7}$$

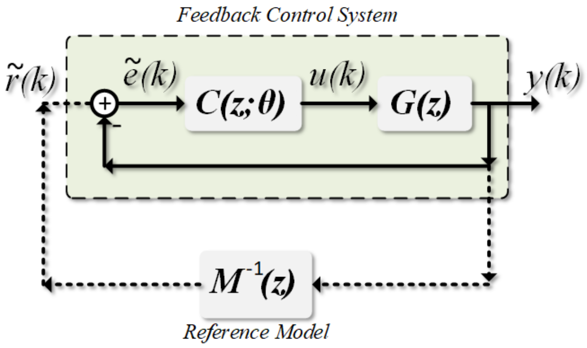

Figure 1. Diagram of virtual reference signal.

where z is the shift operator ($z^{-1}x(k) = x(k-1)$). It should be noted that this *virtual reference* represents the signal that must be applied in reference model $M(z)$ to obtain the output $y(k)$. Considering that the reference model and physical plant have the same signals of reference and output, the virtual error in the physical plant is given by

$$\tilde{e}(k) = \tilde{r}(k) - y(k) \tag{8}$$

With the input ($\tilde{e}(k)$) and output ($u(k)$) signals of the controller ($C(z;\theta)$), the parameters of the controller (θ) are in the solution of the following optimization problem:

$$\theta^* = \arg\min_{\theta} J(\theta) = \arg\min_{\theta} \sum_{k=1}^{N} [u(k) - C(z;\theta)\tilde{e}(k)]^2. \tag{9}$$

4. SVC CONTROL SCHEME

The multilevel control scheme used in this work is composed of the PVC (only local measurements) and the SVC (remote pilot bus measurements). This hierarchical control structure is presented in Figure 2. Practically, the PVC assures the minimum performance level required for the system, and it is located close to the generator plants. The SVC is located at a central level, such the Energy Management System (EMS), to be able to optimize the performance of the local controllers. To reach this goal, the SVC controller must be able to process real-time signals (voltage magnitudes) from selected pilot buses $(y_1(k), ..., y_n(k))$. The voltages of the pilot buses are measured by PMUs and processed by the SVC in order to provide the appropriate control signals to the AVR reference $(u_1(k), ..., u_n(k))$ at each local generator. These control signals must keep the power system voltage profile at a desired threshold.

According to previous works (Sancha et al., 1996), (Arcidiacono, 1983) the structure of the SVC controller must take into account the capability of the generator to control the voltage in a selected pilot bus. This capability is clearly determined by the electrical distance of the generators from the pilot bus. As suggested in Sancha et al. (1996), Arcidiacono (1983) it is better to divide the power system in control areas following the selection of the pilot buses. Additionally, the SVC control design must be coordinated, otherwise some oscillations or even unstable oscillations may show up. These oscillations come from the iteractions between controllers of neighboring areas. In this work the SVC structure to be used is based on the Italian hierarchical voltage control (Cañizares et al., 2005). The secondary level (RVR - Regional Voltage Regulators) includes the reactive power regulator, which is basically integral controls, able to operate to achieve SVR. The primary level includes the classical AVR units already operating in the power plants and a block that. The RVR close the control loops of pilot node voltages, providing each area with a specific reactive power level, one which controls the local power plant's voltage and reactive power regulators called PQR.

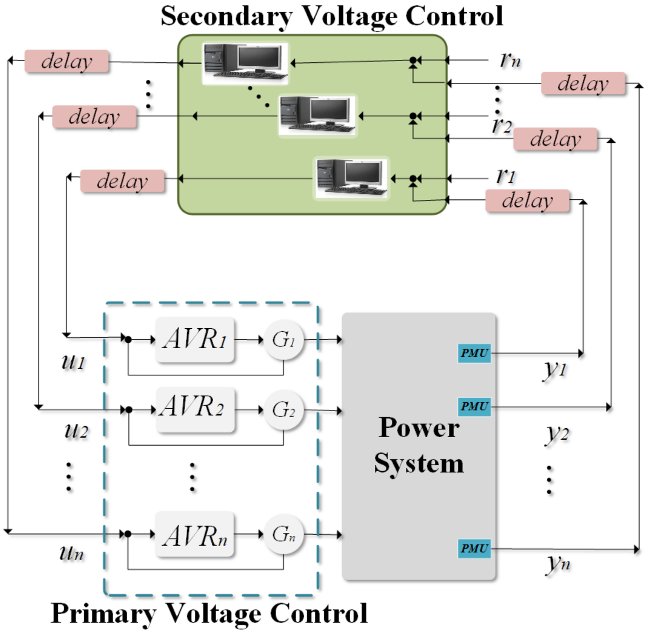

Figure 2. SVC control structure.

5. METHODOLOGY

5.1 Select pilot buses and generators

Selecting the pilot buses is an important part of the SVC design. In this work, the choice of pilot buses was based on the methodologies presented in Zhao and Lu (2018); Gómez et al. (1992). As generators are readily available reactive power sources, additional equipment is not required for the proposed application.

5.2 Probing Signal

Once the pilot buses and generators have been chosen, a probing signal must be applied to obtain the dynamics between the system's inputs (generators) and outputs (pilot buses). The core idea is that the dynamics of pilot bus voltage, under any change in generator reference, should be modeled from the data. In this work, a step signal with controlled amplitude is applied to the AVR of each generator, and then the voltages in the pilot buses are collected by the PMU measurements.

5.3 Reference model

A closed-loop transfer function represents the desired system performance. The choice of parameters that make up the reference model should be driven by process constraints, and input constraints, etc. Fast controllers require high control effort, which can saturate them more easily, while slow controllers may not be efficient under disturbances. The SVC has a slower response when compared with the PVC. Therefore, the reference model $M(z)$ should be defined according to the dynamics expected for the SVC. Based on this, a procedure to automatically determine the appropriate reference model is presented by Gonçalves da Silva et al. (2014), using three different kind of reference models. The model found that will be used in this work is

Model 1:

$$M_1(z) = \frac{1-a}{1-az^{-1}} z^{-nk}, \tag{10}$$

This model represents a desired behaviour with no overshoot, and depends on the process's time delay (nk), and the dominant discrete pole a, which can be computed as follow

$$a = e^{\frac{-4T_s}{t_s}} \tag{11}$$

where t_s is the desired settling time.

5.4 The Initial MFAC Parameters Settings

The following method suggests a complete data-driven initial setting to MFAC controller using the VRFT idea (Roman et al., 2016; Precup et al., 2021). Figure 3 shows the structure with MFAC-VRFT.

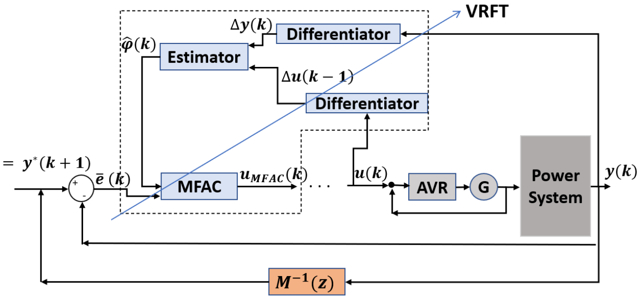

Figure 3. Structure with mixed MFAC-VRFT (adapted from Roman et al. (2016)).

If $\tilde{r}(k)$ specific to VRFT is considered to desired response $y^*(k+1)$ in MFAC, the MFAC controller structure can be considered in a closed-loop, thus the desired response can be estimates as follows

$$y^*(k+1) = M^{-1}y(k) \tag{12}$$

The law control in (4) at the initial point can be rewritten as

$$u_{MFAC}(k) = u_{MFAC}(k-1) + \frac{\hat{\varphi}(1)}{\lambda + ||\hat{\varphi}(1)||^2}[M^{-1}-1]y(k) \tag{13}$$

where the weight factor ρ is set to be 1.

Thus, the goal is to minimize the performance criterion of the signal controller output error

$$\begin{aligned} J(\varphi(1),\lambda) &= \bar{E}[u_{MFAC}(k,\varphi(1),\lambda) - u(k)]^2 \\ &= \bar{E}\Bigg[u(k-1) \\ &\quad + \frac{\hat{\varphi}(1)}{\lambda + ||\hat{\varphi}(1)||^2}[M^{-1}-1]y(k) - u(k)\Bigg]^2 \\ &= \bar{E}\left[\frac{\hat{\varphi}(1)}{\lambda + ||\hat{\varphi}(1)||^2}[M^{-1}-1]y(k) - \Delta u(k)\right]^2. \end{aligned} \tag{14}$$

where a nonlinear least-squares is used to solve this problem. To solve this problem was used the Matlab function *lsqnonlin*, based on trust-region-reflective algorithm.

Therefore, the proposed MFAC control approach translates the design of MFAC algorithm parameters ($\varphi(1)$ and λ) into easier to comprehend closed-loop characteristics described by the reference model M.

6. APPLICATION RESULTS

The IEEE 39 bus power system, which contains 10 generators, is chosen to test the proposed SVC performance, Figure 4. The nonlinear simulations are carried out using Matlab/Simulink software with the power system parameters available in Moeini et al. (2015). Generator 2 is chosen as the slack machine, and it is not included in the SVC.

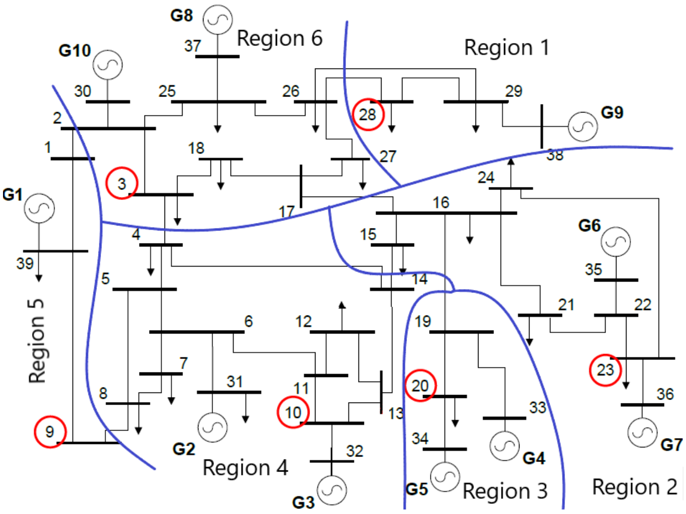

Figure 4. IEEE 39 bus power system diagram.

6.1 Parameters Settings

In this work, the SISO MFAC approach was carried out and compared with a performance of PI controllers tuned using the model based approach and the VRFT approach. The first column in the Table 1 represents the pairs (bus/generator) of each region. The RVR (PI controller) parameters tuned by the model based approach can be found in Cañizares et al. (2005), and the transformer reactance located in each generator bus and the equivalent reactance of each pair (computed using the Thevenin principle) are presented in Table 1. The VRFT-SVC performs a SISO control, where only one generator by region participates. Basically, the parameters used to tune the PI controller using VRFT are the same to initialize the MFAC approach. With the open-loop experiment data, the reference model choice is computed and each pair (bus/generator) reference model has the Model 1 structure, with the sampling time (T_s) chosen as $50ms$ and the desired settling time (t_s) is $50s$. To all pairs the process time delay (nk) and the dominant discrete pole (a) computed was 2 and $0,996007989$, respectively. The estimate controller parameters using the VRFT algorithm and the traditional PI parameters are presented in Table 2.

Table 1. Transformer and equivalent reactance of the pairs (bus/generator).

Bus|Gen	$X_T(p.u.)$	$X_{eq}(p.u.)$
03|10	0,1810	0,0311
09|01	0	0,0250
10|03	0,0200	0,0200
20|05	0,0180	0,0180
23|07	0,0272	0,0272
28|09	0,0156	0,0288

In this work, the MFAC controller is designed to substitute the entire PQR and RVR in the Italian hierarchical voltage control. Thus, an open-loop experiment is carried out, where a step signal ($0.02p.u.$) is applied in the AVR' s reference.The initial parameters $\varphi(1)$ and λ are obtained by solving the equations (12) and (14), and it is shown in Table 2. The other MFAC-VRFT controller parameters (μ, ρ, and η) can make better the controller performance, but in this work, they are set to be 1.

Table 2. Controller parameters.

	VRFT		Traditional		MFAC	
Bus|Gen	K_p	K_i	K_p	K_i	$\varphi(1)$	λ
03|10	0.3190	0.0071	0.2760	0.0077	0.2664	7.4217
09|01	0.2470	0.0122	0.2000	0.0080	0.0860	9.2111
10|03	0.1301	0.0051	0.2500	0.0100	0.1504	8.5975
20|05	0.1098	0.0036	0.2777	0.0111	0.0936	9.1402
23|07	0.1186	0.0048	0.1838	0.0073	0.1621	8.4836
28|09	0.0666	0.0024	0.3205	0.0099	0.0714	9.3481

6.2 Simulation Results

Initially, the reference voltage magnitude is set to 1 p.u. in all pilot buses. The power system voltage requirement is 4%. To preserve the terminal bus of generators against over voltage, a limiter is specified in the AVR output $u(k)$ (20%). Initially, the power system is stable with all buses attending the 4% requirement for voltage magnitude using the PVC (AVRs are set to 1 p.u.) and SVC.

- **Case 1**

A load disturbance with a constant power factor (100% in the active and reactive power) is applied at Bus 27. Note that when compared to the PI VRFT approach, the MFAC has a shorter settling time, but when compared to the traditional PI, it has a longer settling time when the generator is closer to the pilot bus, because the model based controller are strongly dependent on the reactance of the transformer near the generation and the equivalent reactance between the generator and the pilot bus. Figure 5 shows the load disturbance effect in the pilot bus 28 (the most affected pilot bus) using the three different controller approaches. Under disturbance effects, the MFAC approach presents a higher reference signal, which produces a higher overshoot within acceptable limits, due to its derivative effect, and its adaptive parameter that changes to reach a faster response (not shown in this work).

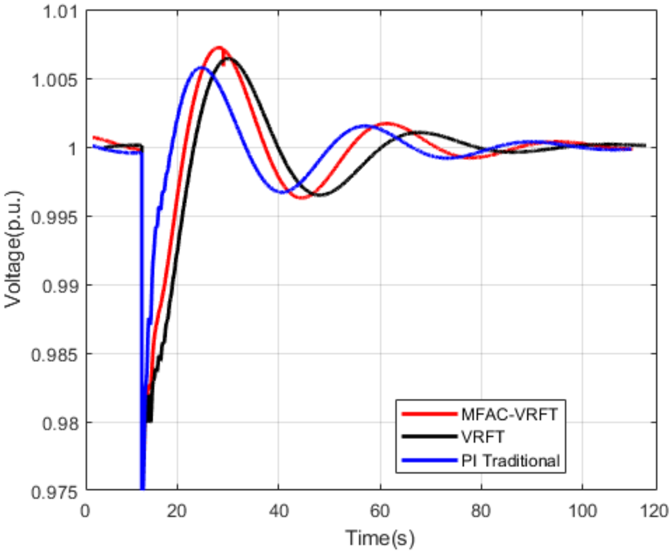

Figure 5. Pilot bus voltage during load disturbance (Bus_{28}).

- **Case 2**

A disturbance in the 3-4 transmission line occurs, leading to the opening of its circuit breakers, and the loss of this line. Figure 6 shows the load disturbance effect in the pilot bus 03 (the most affected bus in the system) using the three different controller approaches. In that case, there is a change in the system's topology, in which the power flows change, and sometimes, the controllers cannot cope, as their design was based on data from a model that did not foresee this physical change. Because of the high voltage variation in this bus, the MFAC controller produces a greater effort on the control signal than the other controllers (not shown in this work).

7. CONCLUSIONS

Model-Free Adaptive Controlers (MFAC) provided a faster response than the previous ones. Its characteristic of adapting its parameter to achieve faster response depends on the derivative of the system's output signal. Therefore, when there is a transient, the MFAC parameter will vary to reach the reference more quickly and optimally. As the MFAC control law depends on the system error, therefore the excursion of the output signal to its reference was greater for disturbances cases. Thus, the controllers of both cases showed greater variations in their parameters. An interesting point to stand out in this work is that although Virtual Reference Feedback Tuning (VRFT) and MFAC have different characteristics and belong to different classes

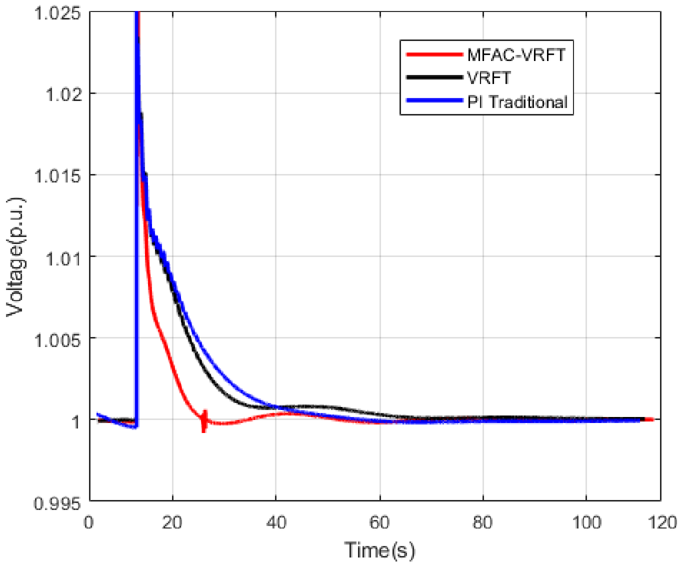

Figure 6. Pilot bus voltage during Transmission Line 3-4 disturbance (Bus_{03}).

of controllers, they proved to be complementary, because a great difficulty in the MFAC method is to find in the literature a procedure regarding the initialization of its parameters. Here was presented a methodology that used the algorithm VRFT in the initialization of MFAC, and its results were satisfactory regarding the voltage limit requirement imposed in this work.

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