Adaptive voltage regulation with harmonic distortion containment objectives in electrical power systems

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Abstract

Control schemes to regulate the nodal voltage profile in electrical power systems often utilize Static VAR systems (SVSs) which directly and locally regulate the voltage amplitude of the busbar at which the SVSs are connected. However, such devices generate harmonic distortion in power systems by injecting harmonic currents. In this context, this paper proposes an adaptive voltage regulation control scheme with optimization strategy, which ensures both the fulfilment of the design requirements imposed on the voltage closed-loop regulation control scheme and the containment of the harmonic distortion levels. Numerical simulations confirm the effectiveness of the adopted control scheme in terms of voltage control performance and harmonic distortion containment.

1 Introduction

In power systems the voltage/reactive power control aims at keeping an adequate voltage profile at all busbars. Several control schemes for voltage/reactive power regulation have been presented in literature [1]. They vary with references to the control architectures according to the degree of centralization versus decentralization, and with reference to the control implementation according to the degree of automation versus manual operation. Generally, the voltage/reactive power control is organized in a three-level hierarchy. The objective of the primary control level is to keep the nodal voltage amplitude at a reference value by controlling the reactive power injection. The secondary control level is based on Regional/area Voltage Regulation (RVR), attained by adjusting the reactive power injections and voltage references of the primary control level. The tertiary one is centralized and aims at system optimal operation with respect to some objectives, such as security and transmission losses.

The primary control level is performed by synchronous generators, Static VAR systems (SVSs) and other devices. In the following, without loss of generality, a Fixed Capacitor - Thyristor Controlled Reactor (FC-TCR) configuration is considered, see Figure 1; its steady-state operating characteristic is shown in Figure 2. Between points A and B the reactors are switched on partially and behave as a variable reactance. The slope of the characteristic determines the

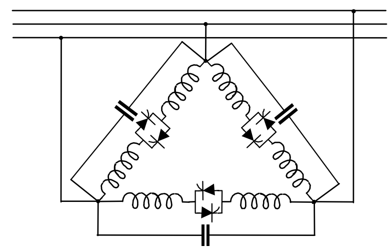

Figure 1: FC-TCR configuration for a SVS.

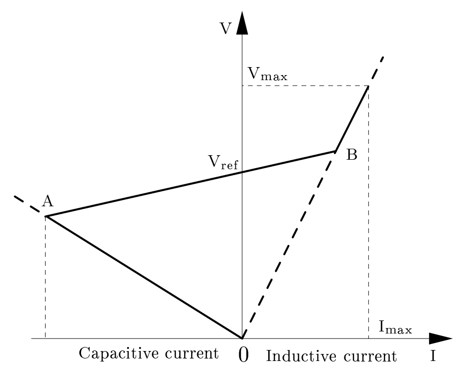

Figure 2: SVS voltage-current operating characteristic.

SVS current variation in response to the bus voltage variation. The voltage reference signal is sent to the SVS voltage regulator by the RVR. Unfortunately, the SVS injects harmonic currents into the power system and their amplitudes are a nonlinear functions of the thyristor firing angle α [2, 9]. Some of the main undesired effects due to the presence of current harmonics are the increase of the losses and the voltage distortion.

To counteract the presence of harmonic currents, expensive filtering actions is introduced into the power system. To help reducing the rating of such filters, this paper proposes an optimization strategy, embedded in an adaptive voltage regulation control scheme. The aim is reducing the amplitude of the harmonic currents injected by the SVS, while the required performance expressed in terms of primary voltage regulation is fulfilled. The proposed strategy is applied to a SVS adaptive control scheme [8] and leads to decreasing the harmonic distortion level. The SVS adaptive

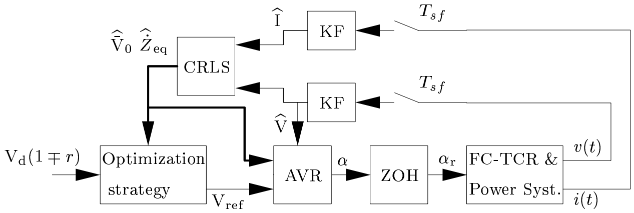

Figure 3: SVS adaptive voltage regulation control scheme with optimization strategy.

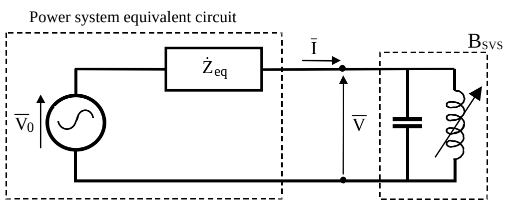

Figure 4: Power system equivalent electrical circuit and SVS.

control scheme with optimization procedure is shown in Figure 3.

After briefly recalling the design approach to the adaptive voltage regulation control scheme, this paper illustrates the proposed optimization strategy. The procedure is based on the solution of a constrained minimization problem whose objective function represents a measure of the distortion level. In particular, the considered objective function is a function of the firing angle via the amplitude of the harmonic currents generated by the SVS. The optimization strategy also realizes an adaptive action with respect to the changes of the power system operating conditions. To test the proposed control scheme in terms of regulation performance and optimization task, numerical simulations have been developed. The reported results confirm the goodness of the implemented control scheme.

2 SVS adaptive voltage regulation

Let consider the adaptive control scheme with harmonic distortion containment objectives shown in Figure 3. The block named "Optimization strategy" computes the reference value $\mathrm{V_{ref}}$ of the nodal voltage to be controlled, which is sent to the Adaptive Voltage Regulator (AVR). As concerns the remaining part of the control scheme in Figure 3 it represents a self-tuning regulator scheme which consists of three main tasks [8].

In the first task, the voltage and current phasors at fundamental frequency are determined starting from the sampled measurements of the nodal voltage $v(t)$ and of the current $i(t)$ which is injected by the SVS. This task is accomplished by adopting a filtering technique based on a discrete Kalman Filter [4, 5] (blocks named KF); in particular, necessary conditions to assure observability and, then, stable estimations are derived in [7].

The second task performs the on-line identification of

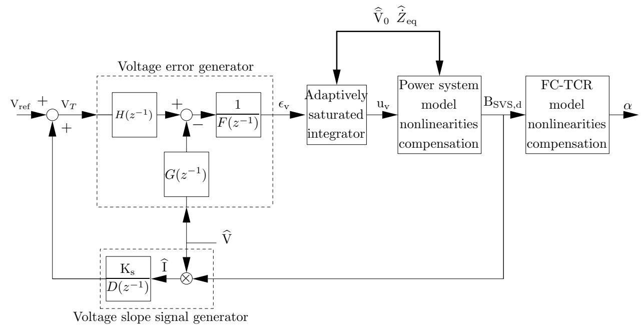

Figure 5: Block scheme representation of the adaptive voltage regulator.

the parameters $\bar{\mathrm{V}}_0$ and $\dot{Z}_{\mathrm{eq}}$ of the Thevenin equivalent circuit representing the electrical power system at the fundamental frequency, see Figure 4. The on-line parameter identification is obtained by adopting classical well-known Recursive Least Squares based technique (see for example [5, 10]), which is extended to take into account physical constraints [7]. The algorithm utilizes the estimates of the voltage and current phasors $(\widehat{\mathrm{V}}, \widehat{\mathrm{I}})$ at the fundamental frequency given by Kalman Filters. In Figure 3 this task is accomplished by the blocks named CRLS (Constrained Recursive Least Squares). Details about different identification techniques used to estimate $\bar{\mathrm{V}}_0$ and $\dot{Z}_{\mathrm{eq}}$ can be found in [6].

The third task concerns the block named AVR in Figure 3, which implements the closed-loop voltage regulation. Its block scheme is represented in Figure 5. The output of the voltage error generator is integrated yielding a voltage command $\mathrm{u_v}$. To obtain the desired value of the SVS equivalent susceptance $\mathrm{B_{SVS,d}}$, an adaptive nonlinear block is used which compensates for the power system model nonlinearities using the estimated values $\widehat{\bar{\mathrm{V}}}_0$ and $\widehat{\dot{Z}}_{\mathrm{eq}}$. Finally, a block compensating for the FC-TCR nonlinear law $\mathrm{B_{SVS}}(\alpha)$ is used to generate the firing angle α. The value $\widehat{\mathrm{I}}$, numerically evaluated from the values of $\mathrm{B_{SVS,d}}$ and $\widehat{\mathrm{V}}$, is fed to a block with gain equal to $\mathrm{K_s}$, which is the required slope of the steady-state characteristic (see Figure 2). Filter $D(z^{-1})$ ensures that the time response of the voltage slope signal generator is higher than the time response of the voltage error generator.

To compensate for the power system model nonlinearities, the required value of the SVS equivalent admittance, $\dot{\mathrm{Y}}_{\mathrm{SVS}}$, must evaluated for a given value of the command signal $\mathrm{u_v}$, being $\dot{\mathrm{Y}}_{\mathrm{SVS}} = \dot{\mathrm{Y}}_{\mathrm{FC}} + \dot{\mathrm{Y}}_{\mathrm{TCR}}$. $\dot{\mathrm{Y}}_{\mathrm{FC}}$ represents the admittance value of the capacitor branch, while it is $\dot{\mathrm{Y}}_{\mathrm{TCR}} = f(\alpha)\dot{\mathrm{Y}}_{\mathrm{R}}$, where $\dot{\mathrm{Y}}_{\mathrm{R}}$ is the total value of the admittance of the reactor branch when no partialization is performed ($f(\alpha) = 1$). The function $f(\alpha)$ assumes values in the range [0, 1]; it is given by [2]

$$f(\alpha) = 2 - 2\alpha/\pi + \sin(2\alpha)/\pi \tag{1}$$

where the firing angle is measured starting from the zero-crossing of the phase-to-phase voltage and $\pi/2 \leq \alpha \leq \pi$.

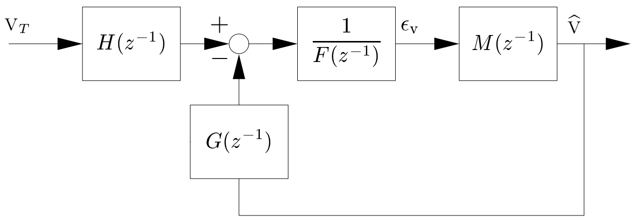

Figure 6: Simplified block scheme used in the voltage error generator design.

For a given value of the command signal $\mathrm{u_v}$, the required value of $\dot{\mathrm{Y}}_{\mathrm{SVS}}$ is evaluated by solving the following problem:

$$\text{find } f(\bar{\alpha}) \in [0,\, 1] : \mathrm{u_v} = \frac{\widehat{\mathrm{V}}_0}{\left|1 + \hat{\dot{Z}}_{\mathrm{eq}}\Big(\dot{\mathrm{Y}}_{\mathrm{FC}} + f(\bar{\alpha})\dot{\mathrm{Y}}_{\mathrm{R}}\Big)\right|}. \tag{2}$$

Notice that the solution of this problem requires the availability of the estimated parameter values given by the CRLS algorithm. The model nonlinearities compensation is then adaptive. Once the value $f(\bar{\alpha})$ is determined, the output $\mathrm{B_{SVS,d}}$ can be directly evaluated as:

$$\mathrm{B_{SVS,d}} = \mathrm{Im}\{\dot{\mathrm{Y}}_{\mathrm{FC}}\} + f(\bar{\alpha})\,\mathrm{Im}\{\dot{\mathrm{Y}}_{\mathrm{R}}\}. \tag{3}$$

In the block of Figure 5 which has as input $\mathrm{B_{SVS,d}}$ and as output the firing angle α, the FC-TCR model nonlinearities compensation is carried out. The task is to determine $\bar{\alpha}$ for a given value of $\mathrm{B_{SVS,d}}$ in (3). Since (1) cannot be solved analitically, a numerical procedure is adopted, based on a look-up table and linear interpolation between subsequent points of the table.

Finally, the voltage error generator design must be performed. The design is carried out under the hypothesis that the power system nonlinear model is fully compensated and the integrator in Figure 5 is not saturated. Let now consider the block scheme depicted in Figure 6. The sampled data transfer function $M(z^{-1})$ between the sequence input $\{\epsilon_{\mathrm{v}}\}$ and the sequence output $\{\widehat{\mathrm{V}}\}$ is given by, (see Figure 3 and Figure 5)

$$M(z^{-1}) = \frac{\widehat{\mathrm{V}}(z^{-1})}{\epsilon_{\mathrm{v}}(z^{-1})} = \frac{Z\Big\{ZOH(s)TCR(s)KF(s)\Big\}}{1 - z^{-1}}$$

where $TCR(s)$ and $KF(s)$ are the transfer functions of the SVS and of the Kalman filter, respectively. They are given by:

$$TCR(s) = \frac{e^{-\mathrm{T_d}s}}{(1 + s\mathrm{T_{TCR}})^2}, \qquad KF(s) = \frac{1}{(1 + s\mathrm{T_{KF}})^2}$$

where $\mathrm{T_d}$ and $\mathrm{T_{TCR}}$ are the delay time and the time constant of the FC-TCR, while $\mathrm{T_{KF}}$ is the time constant of the filter.

The design is based on standard pole assignment technique [5, 10]. Applying this technique, the controller polynomials $F(z^{-1})$ and $G(z^{-1})$ are assigned so as to shift the closed loop poles in some specified locations such that the desired characteristics, expressed in terms of control performance, are satisfied. The polynomial $H(z^{-1})$ ensures a unitary steady-state gain for the closed loop transfer function. In paper [8] the voltage error generator design has been developed so as to guarantee a closed-loop damped step response with a desired value for the settling time.

3 Optimization strategy

In Figure 3, the structure of the SVS adaptive voltage regulation control scheme with optimization strategy is shown. In this scheme, the optimization strategy block receives the voltage reference signal $\mathrm{V_d}$ from the RVR. If the RVR can successfully perform its area/regional voltage regulation allowing the SVS voltage amplitude within an assigned range $[\mathrm{V_{d,m}},\, \mathrm{V_{d,M}}]$ where

$$\mathrm{V_{d,m}} = V_{\mathrm{d}}(1 - r) \qquad \text{and} \qquad \mathrm{V_{d,M}} = V_{\mathrm{d}}(1 + r),$$

then the SVS optimization strategy utilizes such degree of freedom to minimize the harmonic distortion level produced into the power system by the SVS. The quantity r is equal to

$$r = \frac{\Delta\,\mathrm{V}/2}{\mathrm{V_d}}$$

being $\Delta\,\mathrm{V} = \mathrm{V_{d,M}} - \mathrm{V_{d,m}}$ the width of the allowed voltage range.

The first step of the optimization strategy is to transform the assigned boundary values $\mathrm{V_{d,m}}$ and $\mathrm{V_{d,M}}$ in corresponding limit values $\alpha_{\mathrm{m}}, \alpha_{\mathrm{M}}$, with $\alpha_{\mathrm{m}} < \alpha_{\mathrm{M}}$, imposed on the firing angle α. To do this, let's rewrite the equation appearing in problem (2) as:

$$\mathrm{V_{d,M}} = \frac{\widehat{\mathrm{V}}_0}{\left|1 + \hat{\dot{Z}}_{\mathrm{eq}}\Big(\dot{\mathrm{Y}}_{\mathrm{FC}} + f(\alpha_{\mathrm{M}})\dot{\mathrm{Y}}_{\mathrm{R}}\Big)\right|} \tag{4}$$

where the variable u_{v} is replaced by the value $\mathrm{V_{d,M}}$ and the function $f(\alpha)$ is calculated for $\alpha = \alpha_{\mathrm{M}}$. It must be pointed out that equation (4) represents the model of the equivalent system shown in Figure 4 detailed for $\mathrm{V} = \mathrm{V_{d,M}}$. Solve (4) with respect to $f(\alpha_{\mathrm{M}})$. At this point the solution of equation $f(\alpha_{\mathrm{M}}) = 0$, see 1, gives the sought value α_{M}. The same procedure is adopted to obtain α_{m} starting from the value $\mathrm{V_{d,m}}$.

The second step of the optimization strategy concerns with the problem of minimizing, with respect to the variable α, an assigned function $\mathrm{J}[\mathrm{I}_h(\alpha)]$ of the harmonics current $\mathrm{I}_h(\alpha)$ injected by the SVS, with $h = 1 \ldots n$. Among different functions available in literature which give a measure of the distortion level present in the power system, (see for example [3]), the Total Harmonic Distortion has been assumed as function $\mathrm{J}[\mathrm{I}_h(\alpha)]$. It is given by:

$$THD(\alpha) = \sqrt{\sum_{i=1}^{n} \mathrm{I}_h^2} \tag{5}$$

in which [2]

$$\mathrm{I}_h(\alpha) = \frac{4\dot{\mathrm{Y}}_\mathrm{R}}{\pi}\,\mathrm{V}(\alpha)\left[\frac{h\sin(\alpha)\cos(h\,\alpha)-\cos(\alpha)\sin(h\,\alpha)}{h(h^2-1)}\right] \tag{6}$$

being $\mathrm{V}(\alpha)$ the rms SVS voltage given by (4) substituting $\mathrm{V}(\alpha)$ for $\mathrm{V}_{\mathrm{d,M}}$ and α for α_M (see Figure 4). By the way, other distortion level functions can be used as objective function and the adoption of THD index does not influence the generality of the optimization strategy.

The one-dimensional nonlinear problem to be solved in the second step is then:

$$\min_{\alpha}\Big\{THD(\alpha)\Big\} \qquad \text{with} \quad \alpha_\mathrm{m} \le \alpha \le \alpha_\mathrm{M} \tag{7}$$

Let denote with α_{opt} the value resulting from the solution of problem (7). The third step of the proposed strategy aims at determining the reference value $\mathrm{V}_{\mathrm{ref}}(\alpha_{\mathrm{opt}})$. In fact, from the knowledge of α_{opt} it is possible to determine both the value $\mathrm{B}_{\mathrm{SVS}}(\alpha_{\mathrm{ott}})$, through the use of (3) via (1), and $\mathrm{V}(\alpha_{\mathrm{opt}})$ by the right side of equation (4) in which the function $f(\alpha)$ is evaluated at α_{opt}.

Finally, the reference value $\mathrm{V}_{\mathrm{ref}}(\alpha_{\mathrm{opt}})$ is obtained as:

$$\begin{aligned}\mathrm{V}_{\mathrm{ref}}(\alpha_{\mathrm{opt}}) &= \mathrm{V}(\alpha_{\mathrm{opt}}) - \mathrm{K_s}\,\mathrm{I}(\alpha_{\mathrm{opt}}) \\ &= \mathrm{V}(\alpha_{\mathrm{opt}})\Big[1-\mathrm{K_s}\,\mathrm{B}_{\mathrm{SVS}}(\alpha_{\mathrm{opt}})\Big]\end{aligned}$$

It is worthwhile to note that all the three steps of optimization strategy require, see equation (4), the availability of the estimated parameter values $\widehat{\mathrm{V}}_0$ and $\widehat{\dot{Z}}_{\mathrm{eq}}$ output by the CRLS block. That is, topological changes in the power system, leading to variations in the estimated parameter values, are taken into account to generate the reference value $\mathrm{V}_{\mathrm{ref}}$. From this point of view, the proposed optimization procedure realizes an adaptive action.

4 Case studies

The proposed adaptive voltage regulation scheme with optimization strategy has been tested by means of time-domain simulations of the power system shown in Figure 7. The simulation is performed in MATLAB/SIMULINK environment. The three-phase 132 kV - 50 Hz system is assumed to be balanced in all its components. The load L_3 and L_4 are equal to 100 MW and 67 MW, respectively, both with a lagging power factor equal to 0.9; loads are represented by means of shunt resistors and reactances. A 10 MVAR SVS is connected to the bus b_4. Details about the electrical line representation are reported in [6]. Concerning voltages, reference is made in the following to the phase voltage peak values expressed in p.u. (per unit) of the SVS rated voltage base.

Concerning the desired requirements imposed on the adaptive voltage regulation scheme, a desired value of the settling time is chosen equal to 0.140 s with a damping factor equal to 0.9; in addition the desired value of the voltage slope is set equal to 0.005.

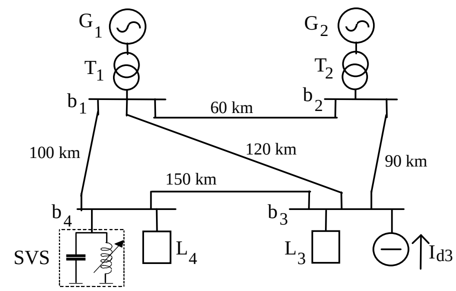

Figure 7: Simulated power system.

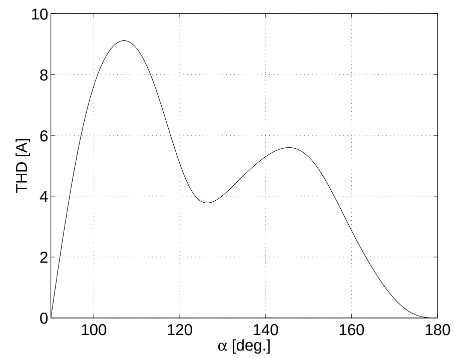

Figure 8: Shaping of the considered objective function THD versus α for the rated operating conditions of the power system.

In the implementation of the self-tuning regulator control scheme shown in Figure 3, it has been chosen, respectively, for the Kalman filters a sampling period equal to $T_{sf} = 10\,\mu$s, for the indentification procedure a sampling period equal to $2.5\,ms$, for the AVR a sampling period equal to 0.6 ms and for the optimization strategy block a sampling period equal to 100 ms.

The assumed objective function to minimize has been determined by considering $h = 5, 7, 11, 13$ in equation (5), that is the $5^{th}, 7^{th}, 11^{th}$ and 13^{th} order harmonics of the current injected by the SVS. For sake of clarity, in Figure 8 it is reported the diagram of the objective function versus the firing angle $\alpha \in [\pi/2, \pi]$, assuming the rated operating conditions for the power system.

Different simulations have been run to test the performance of the adaptive voltage regulator control scheme in presence of the optimization strategy task. These studies are aimed at analyzing two types of effects. On one side, the introduction of the optimization strategy should improve the SVS steady state operation in terms of reduction of harmonic pollution levels; on the other side, it should not worsen the dynamic performance of the adaptive voltage regulator.

Concerning the reduction of the harmonic distortion

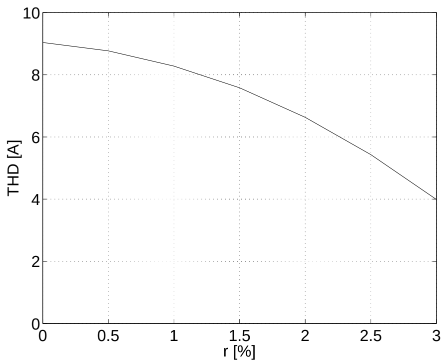

Figure 9: Objective function THD versus r%. Case of $\mathrm{V_d} = 0.78$ p.u..

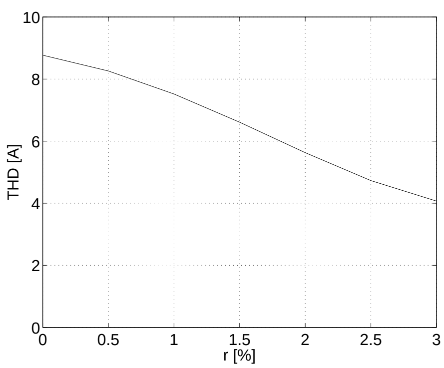

Figure 10: Objective function THD versus r%. Case of $\mathrm{V_d} = 0.79$ p.u..

level, it is evident from (7) that the possibility to reduce the harmonic pollution levels depends on the values α_m and α_M. Each one of these values is obtained by solving (4) and consequently depends on both the operating conditions of the power system, through $\widehat{\mathrm{V}}_0$ and $\hat{\hat{Z}}_\mathrm{eq}$, and on the width of the voltage range $[\mathrm{V_{d,m}},\, \mathrm{V_{d,M}}]$ allowed by the RVR. For these reasons it is useful to represent, for imposed rated operating conditions of the power system, the values assumed by the THD versus different values chosen for r, that is versus different values allowed for $\Delta\mathrm{V}$. In particular, in Figure 9 and in Figure 10 the THD diagram is reported versus the value of r, for $\mathrm{V_d} = 0.78$ p.u. and $\mathrm{V_d} = 0.79$ p.u.,respectively. These Figures have been numerically built by collecting the final THD values obtained by simulating the considered system for different values of r. The resulting points have been linearly interpolated. Obviously, in the case $r = 0$ ($\mathrm{V_{d,m}} = \mathrm{V_{d,M}} = \mathrm{V_d}$) no optimization can be performed.

From the analysis of Figure 9 and Figure 10 it can be recognized that the THD shaping depends on the value of $\mathrm{V_d}$ and that the optimization strategy can significantly reduce harmonic pollution levels provided that a wide voltage range is allowed by the RVR. In fact, by considering for example Figure 9, the value of the THD function is decreased from 9 A, corresponding to $r = 0\%$, to 4 A, corresponding to $r = 3\%$ ($\Delta\,\mathrm{V} = 0.0468$ p.u.). The reduction of the harmonic distortion level is then equal to 56% in the case of $r = 3\%$. Similar considerations can be made from the analysis of Figure 10.

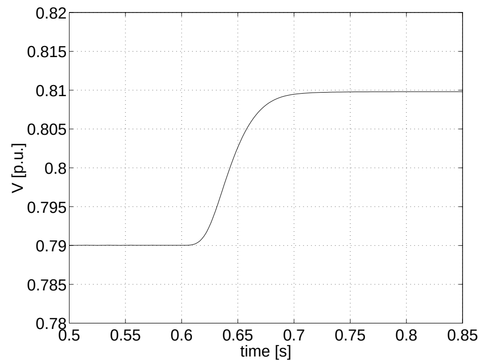

Figure 11: Time variation of the SVS voltage in response to a step variation of r from 0 to 2.5% ($\mathrm{V_d} = 0.79$ p.u.).

Finally, it has been tested that the introduction of the optimization strategy does not alter the adaptive voltage regulator performance. To this aim, in Figure 11 it is reported the time evolution of the SVS voltage in response to a step variation of r. In particular, at $t = 0.6$ s, the RVR changes the value of r from 0 to 2.5% while $\mathrm{V_d} = 0.79$ p.u.. Consequently, the optimization strategy generates a step variation of the voltage reference $\mathrm{V_{ref}}$ sent to the AVR. In this case the optimal value is $\mathrm{V}(\alpha_\mathrm{opt}) = \mathrm{V_{d,M}} \simeq 0.81$ p.u.. The transient response shown in Figure 11 fulfills the requirements assigned in the design phase of the AVR.

Since the optimization strategy uses the estimated values of the parameters of the Thevenin equivalent circuit, the adaptivity of the control system with respect to a variation of the power system operating conditions has been tested. In particular, in Figure 12 it is shown the time evolution of the SVS voltage in response to a step variation of the load L_3. Starting from the final operating conditions shown in Figure 11 ($\mathrm{V_d} = 0.79$ p.u. and $r = 2.5\%$), at $t = 1$ s the load is increased by 10% and, consequently, the SVS voltage suddenly decreases. The AVR promptly acts to support the controlled voltage yielding a transient which lasts about 0.2 s. In the meantime, the optimization strategy evaluates the new reference value to minimize the THD. From the analysis of Figure 12 it is quite apparent that at $t = 1.2$ s a new reference value is sent to the AVR; such value is finally reached by the SVS voltage at about $t = 1.3$ s.

5 Conclusions

The paper has shown that the proposed SVS adaptive voltage regulation control scheme with optimization strategy allows to regulate the nodal voltage profile while limiting the distortion levels due to the presence of harmonic currents. The regulation task is achieved by implementing a self-tuning regulator control scheme with an optimization strategy. The latter calculates the

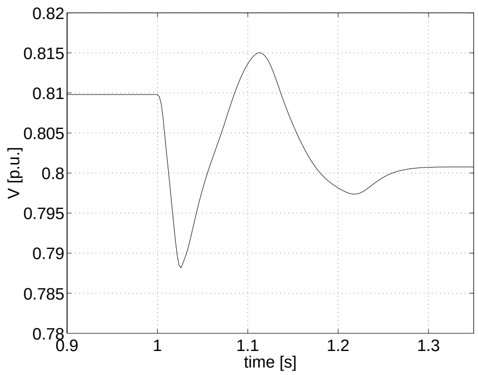

Figure 12: Time variation of the SVS voltage in response to a 10% step variation of load L_3.

voltage reference value by solving a constrained minimization problem, in which the objective function is an assigned function of the harmonic currents. Simulation results confirm the goodness of the proposed control scheme.

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