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SVC Physics-informed adaptive Fuzzy control for Voltage stability in THT networks

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Abstract

Weak electrical networks, sensitive to reactive power variations and low short-circuit power, face voltage stability challenges, especially with industrial loads and multiple disturbances. Standard PI regulators for SVCs have limited performance under these conditions. This article presents an adaptive control strategy, based on the physical relationships between voltage and reactive power, and implemented via a fuzzy logic system. This approach allows a robust regulation without precise network model. Tested on the industrial network of Maloukou, with severe conditions (load variations up to 35 MW, imbalances and dynamic disturbances), it is compared to a conventional SVC and an SVC with PI regulator. The results show a significant improvement in the voltage profile, a reduction in losses, a better power factor and a faster response. It is found that this approach is robust and relevant for weak and disrupted electrical networks.

Keywords: SVC Physics-informed, Fuzzy, Voltage, THT networks.

Introduction

So-called "weak" power grids are common in industrial environments and power systems in developing countries. They are characterized by low short-circuit power, high R/X ratios and limited reactive power support capability. These properties increase their vulnerability to load variations, voltage imbalances, and dynamic disturbances, increasing the risk of voltage instability and power qualitydegradation[1,2]. The voltage stability directly depends on the balance between injected reactive power and local demand. Insufficient compensation can lead to voltage drops or collapse, especially when integrating large process loads[4-6]. The Q–V dynamics thus constitute a central element in the analysis of weak networks. To improve the voltage profile and enhance stability, FACTS devices, and in particular the static reactive power compensator (SVC), are widely used. The SVC offers fast voltage regulation by adjusting its equivalent susceptance[7].

However, classical control strategies, such as PI regulators, show limits with respect to non-linearities and uncertainties[8,9]. Advanced approaches based on artificial intelligence, including fuzzy logic and neural networks, have demonstrated significant improvements in robustness and dynamics[11,12]. However, most remain heuristic and do not explicitly rely on fundamental physical laws, which limits their interpretability. Recent work has explored the use of SVC to improve voltage stability in industrial networks[13,14]. However, few studies propose aunified formulation linking SVC control to physical equations in a robust adaptive framework.

In this context, this paper presents a physics-informed adaptive fuzzy control strategy for SVC control in a weak network. The efficiency is validated on the real industrial network of Maloukou, subjected to severe conditions, and compared to classical strategies, highlighting significant gains in stability, dynamics and energy efficiency.

Nonlinear modeling and formulation of the control problem

Voltage–Reactive Power Modeling: In weak electrical networks, voltage stability is governed by the non-linear coupling between voltage and reactive power.

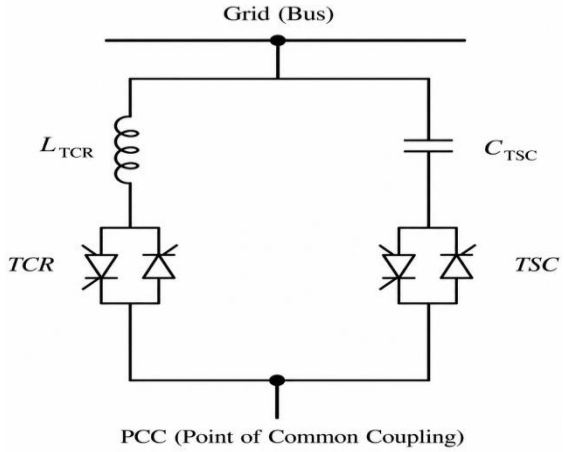


Figure-1: Schematic diagram of an SVC.

Considering an equivalent node powered by a Thévenin source, reactive power is written:

$$Q = \frac{V(V-E)}{X_{eq}} \quad (1)$$

The dynamics of the voltage can then be expressed as:

$$\frac{dV}{dt} = \frac{X_{eq}}{2V-E}\frac{dQ}{dt} \quad (2)$$

The SVC compensator injects a controlled reactive power:

$$Q_{SVC}(t) = -V^2(t)B_{SVC}(t) \quad (3)$$

By drifting: $\frac{dQ_{SVC}}{dt} = -2VB_{SVC}\frac{dV}{dt} - V^2\frac{dB_{SVC}}{dt}$ (4)

By substituting in the dynamics of tension:

$$\frac{dV}{dt} = -K(V, B_{SVC})\frac{dB_{SVC}}{dt} \quad (5)$$

avec: $K(V, B_{SVC}) = \frac{X_{eq}V^2}{(2V-E)+2X_{eq}VB_{SVC}}$ (6)

Formulation of the control problem: The goal is to regulate the voltage around V*ref*:

$$\lim_{t\to\infty} V(t) = V_{ref} \quad (7)$$

The error is defined by:

$$e(t) = V_{ref} - V(t) \quad (8)$$

And $\dot{e}(t) = -\frac{dV(t)}{dt}$ (9)

The reactive power balance gives:

$$C_{eq}\frac{dV(t)}{dt} = Q_{SVC}(t) - Q_{load}(t) \quad (10)$$

are: $\frac{dV(t)}{dt} = \frac{1}{C_{eq}}\left(-V^2(t)B_{SVC}(t) - Q_{load}(t)\right)$ (11)

The order problem is to determine:

$$B_{SVC}(t) = F\left(e(t), \dot{e}(t)\right) \quad (12)$$

Under constraints: $B_{min} \le B_{SVC}(t) \le B_{max}$ (13)

Physics-informed adaptive fuzzy control

The control law of the SVC is defined as a non-linear function of the voltage error and its derivative:

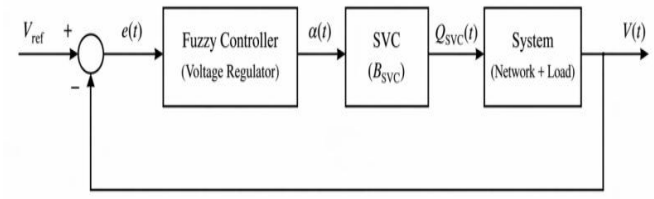


Figure-2: SVC dynamic loop diagram showing V(t), Q(t), a(t).

V_ref: Reference voltage, e(t): Voltage error, α(t): Control signal (firing angle for TCR/ switching for TSC), B_SVC : Equivalent susceptance provided by SVC, Q_SVC(t): Reactive power injected/absorbed by the SVC, V(t) Bus voltage.

$$B_{SVC}(t) = F\left(e(t), \dot{e}(t)\right) \quad (17)$$

The function F(·) is approximated by an adaptive fuzzy inference system of type Mamdani , based on variables e (t) and e ̇(t). The controller writes:

$$B_{SVC}(t) = \sum_{k=1}^{N} \mu_k(e, \dot{e})\, b_k \quad (18)$$

System settings are adjusted inline according to:

$$\dot{\theta} = -\gamma\, e(t)\, \phi(t) \quad (19)$$

Susceptance is subject to physical constraints:

$$B_{min} \le B_{SVC}(t) \le B_{max} \quad (20)$$

The control surface of the fuzzy Mamdani engine is an implicit function defined by the composition of the rules, the degrees of membership of the inputs and the mode of defuzzification (center of gravity). It is obtained by scanning e(t) and Δ e(t) on a discrete grid, evaluating the fuzzy motor for each torque, then represented by the command.

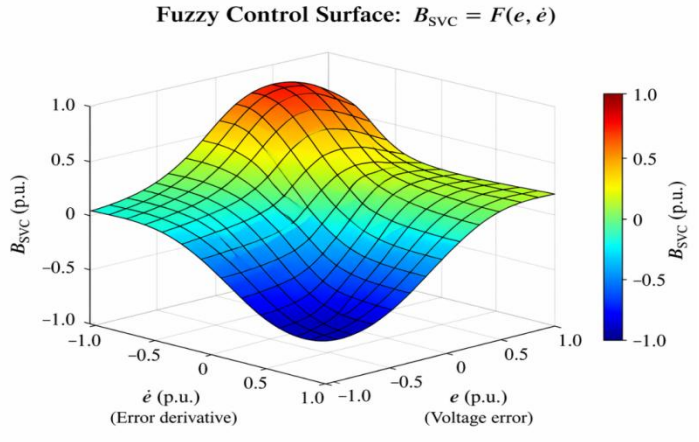


Figure-3: 3D fuzzy control surface of the Mamdani regulator applied to the SVC.

Stability analysis

This section analyzes the stability of the closed loop system by considering the dynamics of the regulatory error and the effect of the fuzzy approximation on convergence.

We consider the regulatory error:

$$e(t) = V_{ref} - V(t) \quad (21)$$

From the reactive power balance:

$$C_{eq}\frac{dV(t)}{dt} = Q_{SVC}(t) - Q_{load}(t) \quad (22)$$

We introduce an ideal law B^* (t) such that:

$$V^2(t)B^*(t) + Q_{load}(t) = -k\,e(t), \quad k > 0 \quad (23)$$

The fuzzy controller approximates this law:

$$B_{SVC}(t) = B^*(t) + \tilde{B}(t) \quad (24)$$

The error dynamic is then written:

$$\dot{e}(t) = -\frac{k}{C_{eq}}e(t) + \frac{V^2(t)}{C_{eq}}\tilde{B}(t) \quad (25)$$

We consider the Lyapunov function:

$$V_L = \frac{1}{2}e^2(t) \quad (26)$$

Its derivative checks:

$$\dot{V}_L = -\frac{k}{C_{eq}}e^2(t) + \frac{V^2(t)}{C_{eq}}e(t)\tilde{B}(t) \quad (27)$$

Under the assumption:

$$\left|\tilde{B}(t)\right| \le \varepsilon \quad (28)$$

we get:

$$\dot{V}_L \le -\frac{k}{C_{eq}}e^2(t) + \frac{V_{max}^2}{C_{eq}}|e(t)|\varepsilon \quad (30)$$

The system is ultimately uniformly bounded. When ε→0, we have:

$$\dot{V}_L \le -\frac{k}{C_{eq}}e^2(t) \quad (31)$$

Simulation Scenarios

The performance of the proposed system is evaluated on an equivalent. Thé venin-type network integrating a SVC controlled by an adaptive fuzzy controller. The parameters are set according to the modeling assumptions, with a reference voltage maintained at V ref=1 p.u. and asusceptance constrained by Bmin ≤ BSVC(t) ≤ Bmax. The performance of the controller is analyzed from the evolution of the voltage at the coupling point, the regulation error e(t), as well as the reactive power injected by the SVC. Three representative scenarios are considered:

Scenario-1: Load variation: A sudden change in the load reactive power Q_load(t) is applied to assess the controller's ability to maintain voltage around its reference value (Figure-4).

Scenario-2: Voltage disruption: A voltage drop is imposed at the equivalent source in order to test the system's robustness against grid disturbances (Figure-5).

Scenario 3: Parametric variation: The system parameters, notably X_eq and C_eq, are modified in order to analyze the controller sensitivity to modeling uncertainties (Figure-6).

The results are compared to those of a classical PI control in order to evaluate the performance of the proposed approach in terms of speed of response, regulation accuracy and robustness against disturbances.

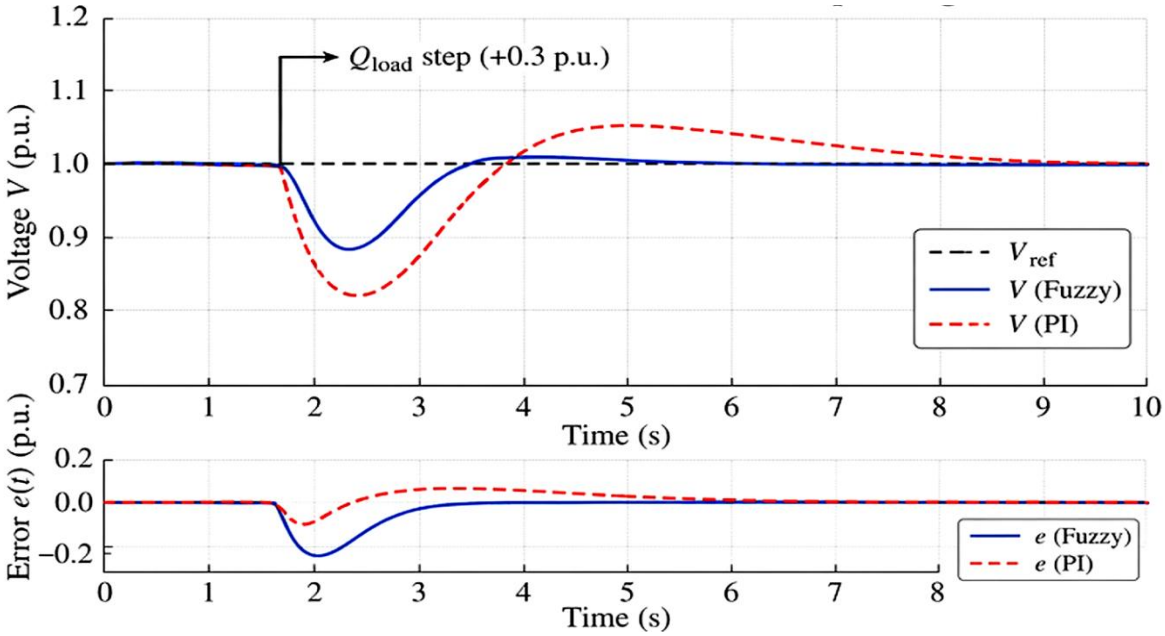


Figure-4: Bus voltage response to a reactive load step change.

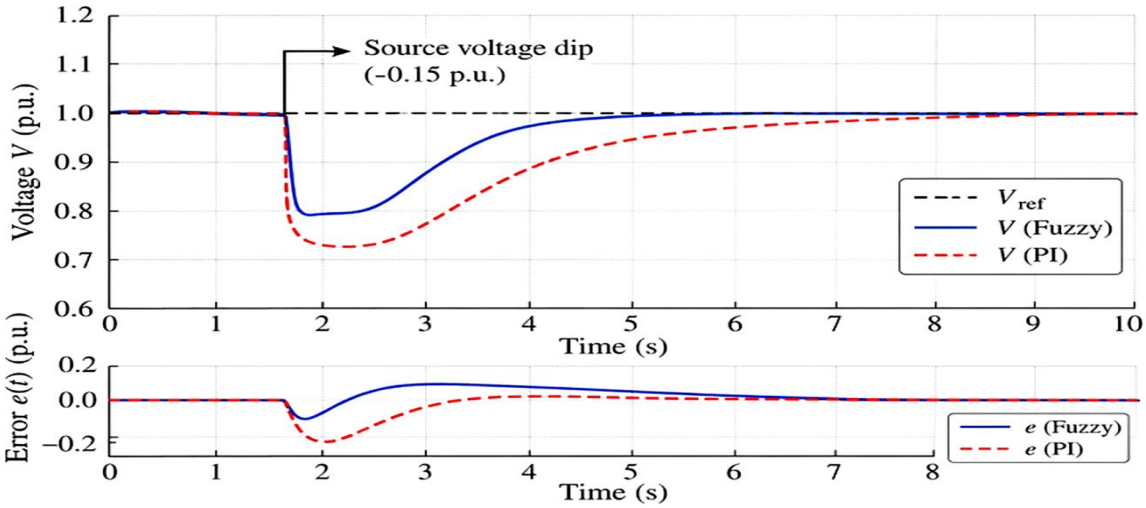


Figure-5: Bus voltage response to a source coltage dip.

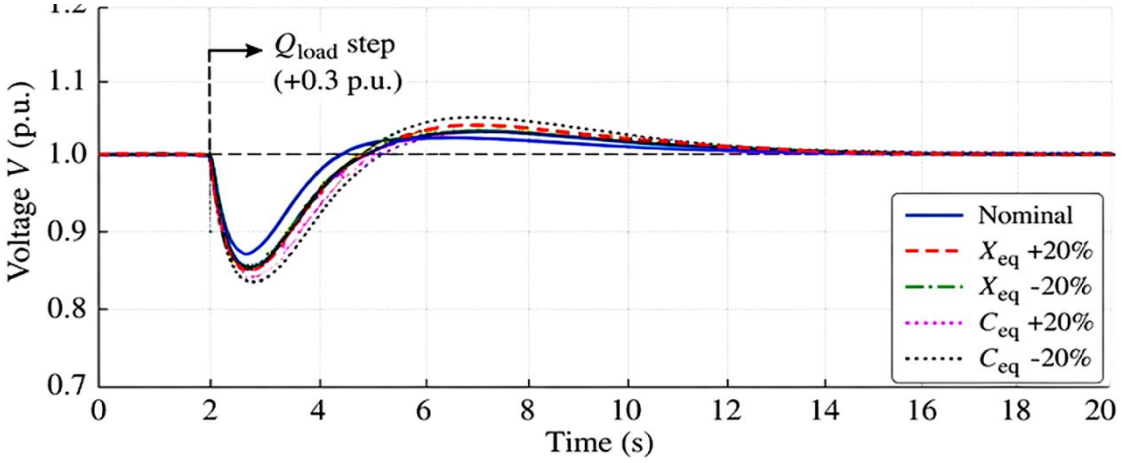


Figure-6: Bus voltage response for different parameter variation.

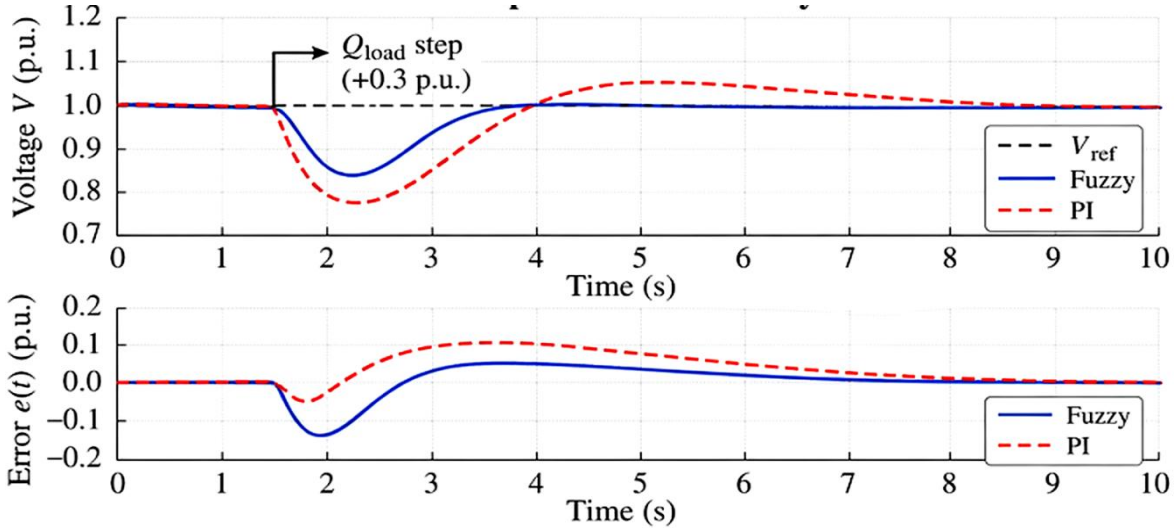


Figure-7: Comparison of PI and Fuzzy Controllers.

Results and Discussion

The performance of the system is evaluated from the temporal responses of the voltage at the coupling point, the regulation error and the reactive power injected by the SVC. In the load variation scenario (Figure-4), the fuzzy controller ensures a rapid return of the voltage to its reference value, with limited overshoot and reduced transient error. The PI control has a slower dynamics and greater deviations in transient mode. In the presence of a voltage disturbance (Figure-5), the fuzzy logic-controlled system shows better compensation capability, characterized by faster recovery and effective attenuation of the voltage drop. Conversely, the PI control has a higher stabilization time. The robustness analysis (Figure-6) highlights the low sensitivity of the fuzzy controller to parametric variations. The different tested configurations lead to similar responses, which confirms the stability and robustness of the proposed approach. Finally, the direct comparison between the two control strategies (Figure-7) shows that the fuzzy controller offers better overall performance, with faster convergence, increased accuracy and better management of disturbances.

Conclusion

This article proposes a voltage regulation strategy based on an adaptive fuzzy controller applied to an SVC in a weak power grid. From a non-linear voltage–reactive power model, a robust control law was formulated. Stability analysis, based on Lyapunov, shows that the closed loop system is uniformly bounded ultimately, ensuring error convergence in the presence of uncertainties. The simulation results highlight superior performances compared to a PI control, in terms of speed, accuracy and robustness against perturbations and parametric variations. These results confirm the interest of the approach for voltage regulation in weakly meshed networks. Future work will focus on real-time implementation and extension to multi-node systems.

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