Intelligent Voltage Regulator to Distributed Voltage Control in Smart Grids

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Abstract—**Distribution networks have, in general, the electrical energy flow unidirectional from substation to customers. With high levels of distributed energy resources integration, the energy may flow backwards which creates challenges with legacy circuit designs and control techniques. The Distribution System Operator fixes a set-point and prepares scenarios and ranges based on seasonal load curves. However, the growing of distributed energy resources, distributed storage, flexible load and plug-in-electrical vehicles brings to the distribution systems substantial challenges. On one hand, the uncontrolled charging load may occur coincidentally with the peak hours. On the other hand the photovoltaic and wind generation may occur coincidentally with the off-peak hours and will affect or even deteriorate the operation performance of distribution systems dramatically. In both cases, the voltage regulators need to have their settings previously evaluated for these different operating conditions. From these considerations, this paper presents an innovative methodology to distributed voltage control developed to a Brazilian power utility (CEEE-D) from the project named Intelligent Dynamic Control for Voltage Regulators and Supervisory Systems in a Smart Grid Environment Code ANEEL PD-5707-4301/2015. The methodology is not restricted to voltage regulators settings. It acts also evaluating the hierarchy between the voltage regulators, adjusting the delay time, based on the network topology. The results are provided using a typical utility distribution circuit from Electrical Energy State Company-CEEE-D. Moreover, the authors discuss further opportunities and challenges in this field of research.**

Index Terms—voltage regulator, voltage control, smart grids, on load tap changer, quality, power supply, fuzzy logic, automation, distributed energy resources, flexible load.

I. INTRODUCTION

Considering the current evolution of electric power systems and the gradual implementation of distribution automation resources, telemetry, advanced algorithms for reconfiguration, load forecasting, micro and distributed mini generation, among others, voltage control has a fundamental role in the application and maintenance of these important resources in distribution system [1], [2].

The execution of maneuvers for the reconfiguration of feeders is a common and necessary activity in urban feeders, generally represented by shorter and more heavily loaded networks. On the other hand, rural or more extensive feeders, who serve several smaller municipalities throughout their area of operation, generally have their topology altered due of eventual contingencies or in cases of scheduled shutdowns. In these cases the voltage regulators must have their adjustments previously evaluated for these different operating conditions [3], [4], [5].

In addition, the seasonal variations of the load and the changes occurring throughout the day such as the transitions between the load levels, presence of distributed generation, the exit of large blocks of load at peak times and the return of these same loads after the end of the hourly range due time of use tariffs, have a significant impact on voltage levels [6], [7].

This paper presents the developments that are being carried out by State Electricity Distribution Company (CEEE-D) and Federal University of Santa Maria (UFSM) with incentives from the Electrical Energy National Agency through ANEEL Research and development (R&D) project ANEEL Code PD-5707-4301/2015 named “Intelligent Dynamic Control for voltage regulators and supervisory systems (CDI-RT) in a smart grid environment”. This R&D project continues the evolution process and maturation of research carried out in the R&D project finished in 2013 named “Efficient use of the innovative potential of smart grids in the improvement of the management of the quality of electric energy in distribution systems”, developed by Federal University of Santa Maria (UFSM) and CEEE-D. The objective is to develop a head series design of an intelligent dynamic controller for voltage regulators (CDI-RT) that can operates automatically based on the commands coming from the developed methodology. The aim is to contribute to increase the operational efficiency of the voltage regulators installed in the distribution systems and improve the quality of the offered services, reduce the costs associated with the displacements of teams for parameterization and adjustments of the voltage regulators and reduction of penalties for voltage levels violations. The TAP Eletro Company is a partner of this project and will contribute in the manufacture of the head series design.

The CEEE-D concession area comprises long feeders, seasonal and rural loads, as well as urban loads, thus the methodology developed allows real-time definition of the voltage regulator settings for the various network topologies and scenarios Whether from maneuvers or from seasonal variations in feeder load. However, the methodology is not

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restricted to the definition of equipment adjustments, it also evaluates the hierarchy between the voltage regulators (RTs), adjusting the timing and limits based on the network topology. It acts as a centralized control by taking control of regulators by sending commands to the regulators and ensuring a more adequate response at the system level.

Next, the main functionalities of the methodology will be presented, highlighting the steps of local control, hierarchical matrix and triggers for the activation of the control functions. Afterwards, the results obtained with the application of the method are demonstrated through a case study.

II. ADJUSTS REQUIRED FOR VOLTAGE REGULATORS

Voltage regulators (VR) are often installed in distribution networks, either urban or rural, to regulate the voltage at each phase of the network separately, in order to maintain voltage within a defined range of values, respecting safe operating limits at the load. A voltage regulator, whose diagram is shown in Fig. 1, is essentially an autotransformer with many TAPs. It has a control system that is responsible for the TAP changing whenever the voltage at the regulator output violates the predetermined limits. Similar to the on load TAP changing transformer (OLTC), the TAP changing is done under load, that is, without interruption of the energy supply. Recently many articles have studied the impact of distributed generation sources on feeders and the importance of voltage regulators to maintain voltage levels within established standards [8].

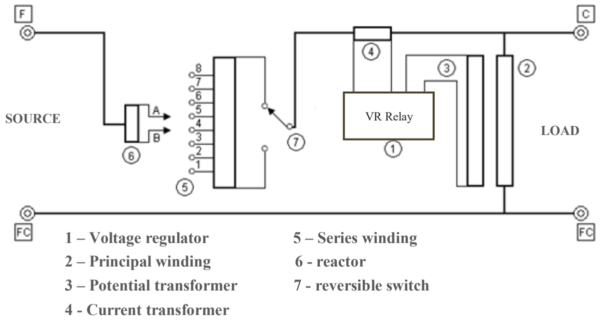

Fig. 1. Voltage regulator basic diagram.

The setting of the voltage regulator settings in a distribution feeder takes into account the location of the equipment, the voltage and load levels at the installation point, the restrictions for the operating range (based on the TAP zones), the existence of upstream and downstream voltage regulators of the equipment considered [8], [9]. In addition to these factors, it is also important to identify the type of load and its seasonability, the load and voltage variations which the system is subject to [10], [11]. Some of these factors can be seen in Fig. 2.

From the evaluation of these factors the experts establish the values of reference voltage, insensitivity range, resistive and reactive compensation coefficients, timing, timing type and regulation range.

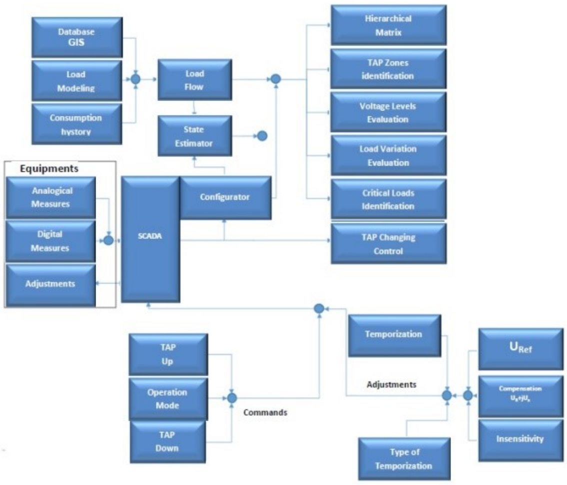

Fig.2. Influence factors for centralized control of VRs.

There are methodologies and algorithms that allow a definition of these parameters, however, in case of system reconfiguration or actions that result in changes on the load or even cause a reverse load flow on the regulator, the operating conditions of the network may no longer be valid for the established parameters [12]. Fig. 3 represents some of the possible conditions verified in each regulator due to changes in the network topology.

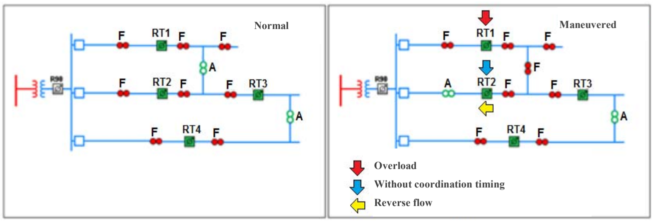

Fig. 3. Power Flow, loading, timing conditions for the Voltage Regulators.

The adjustments should therefore be re-evaluated, or interventions must be performed on the equipment to avoid improper operation, possible inadequate charging or improper voltage levels.

It is possible to adapt the equipment to the conditions of overload, incoordination and reverse flow, by means of the intervention in the equipment be it re-mote or local. The operation of the regulators with high load, above nominal is also possible as long as the adjustment range is restricted. This condition is also possible by the adequacy of the limits of each voltage regulator, associated with the basic parameters of reference voltage (U_{ref}) and resistive (U_r) and reactive (U_x) compensation. In order to coordinate the timing, a hierarchical evaluation of the new configuration is necessary and for the reverse flow operation, the voltage and load limits must evaluated again to make the adjustments in this condition.

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III. CALCULATION OF THE ADJUSTMENTS PARAMETERS

Proper operation of the voltage regulators depends on the correct settings of your parameters, especially the reference voltage, insensitivity, line drop compensation, timing and timing type. The automatic definition of these adjustments is accomplished through the application of a set of equations associated with a State Estimator. The values of U_{ref}, U_R and U_X are calculated from equations (1), (2) and (3).

$$U_R = \frac{\dfrac{(U_{PMax} - U_{PMin})}{RTP}}{\dfrac{I_{PMax}}{RTC}} \cos(\varphi_{PMax}) \tag{1}$$

$$U_X = \frac{\dfrac{(U_{PMax} - U_{PMin})}{RTP}}{\dfrac{I_{PMax}}{RTC}} sen(\varphi_{PMax}) \tag{2}$$

Where:

U_{PMax} : desired voltage on the maximum demand level;

U_{PMin} : desired voltage on the minimum demand level;

φ_{PMax} : maximum power fator angle;

I_{PMax} : current on the maximum demand level;

RTP : potential transformer ratio;

RTC : current transformer ratio.

From the compensation values, the reference voltage is set according to equation (4):

$$U_{REF} = \frac{\left(U_{PMax} - \left(\dfrac{I_L(U_R)\cos\varphi}{I_C} + \dfrac{I_L(U_X)sen\varphi}{I_C} \right) \right)}{RTP} \tag{4}$$

Where:

I_C : primary nominal current;

I_L : nominal line current.

To define the desired voltage at each step, the TAP zone in the downstream of each voltage regulator is used as a restriction. This technique is also used to define the adjustments in case of reversed flow, however in this condition the TAP zone of the transformers upstream of the regulator must be verified.

The TAP zone verification, which can be performed by different methods, basically consists of the TAP definition that presents the least number of voltage transgressions in the secondary network, from the voltage levels received on the primary side of each distribution transformer at different loading levels.

The timing setting depends on the hierarchical control. Initially, it is considered that the regulators closest to the SE should have a faster response than the others. Knowledge about the typology of loads in each control zone provides conditions for choosing the type of timing, where more significant loads, such as large engines, need a faster response, such calculation of adjustment parameters during harvesting periods, for example.

A. *Fuzzy Controler*

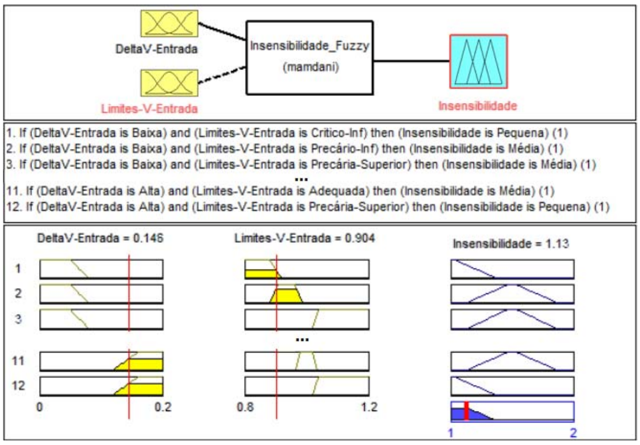
A Fuzzy controller coupled with a heuristic method was developed to define and set the best parameters of voltage reference (U_{Ref}), line drop compensation (U_R e U_X) and .dead band (DB).

Starting from the values read from the memory controller, the adjustments are calculated. These parameters are U_{REF} as equation (4), U_R using equation (2) and U_X using equation (3).

Once modified the time tuning parameters, the local control sends, to the centralized control, the configuration established for validation of the hierarchy. At this moment the processing is performed by returning the set of valid parameter together with the timing indicated. The value and type of delay are defined only by centralized control, to know the hierarchy of controllers along the distribution network.

The major advantage of the application of local control, lies in the fact that the distributed processing control parameters is possible, since each regulator sets its own settings. Another important point to consider is that even in a condition of lack of communication with the centralized system, the adjustments at a local level continue to be processed, defined and sent to regulators as the local processing unit is coupled to the regulator control.

To calculate the insensitivity (DB), the regulatory limits and the analysis of the variation of the input voltage are used, employing for that the fuzzy logic, illustrated in Fig. 4.



1. If (DeltaV-Entrada is Baixa) and (Limites-V-Entrada is Critico-Inf) then (Insensibilidade is Pequena) (1)
2. If (DeltaV-Entrada is Baixa) and (Limites-V-Entrada is Precário-Inf) then (Insensibilidade is Média) (1)
3. If (DeltaV-Entrada is Baixa) and (Limites-V-Entrada is Precária-Superior) then (Insensibilidade is Média) (1)

...

11. If (DeltaV-Entrada is Alta) and (Limites-V-Entrada is Adequada) then (Insensibilidade is Média) (1)
12. If (DeltaV-Entrada is Alta) and (Limites-V-Entrada is Precária-Superior) then (Insensibilidade is Pequena) (1)

Fig. 4. Insensitivity Band Definition.

For a regulator located at a node with low variation and good load, regulation insensitivity can be high. At locations with high load variation and good regulation, it is recommended an average insensitivity and at the other extreme, networks with high load variation and a bad regulation, insensitivity should be low. The values of insensitivity vary depending on the equipment, but are associated with the step size that each TAP offers, being related to the insensitivity low ± 1TAP, average given by ± 1.5TAP and a high insensitivity to values around 2TAP.

IV. DEVELOPED ANALYTIC MODEL

To simulate and analyze the methodology over different scenarios and situations, a model was developed on Matlab/Simulink. A *13 Node Test Feeder System* from IEEE was chosen as initial network to be analyzed and over this base system a Distributed Generation, Step Voltage Regulator and Supervisory Control and Data Acquisition were implemented. The Fig. (5) shows a complete diagram of the network.

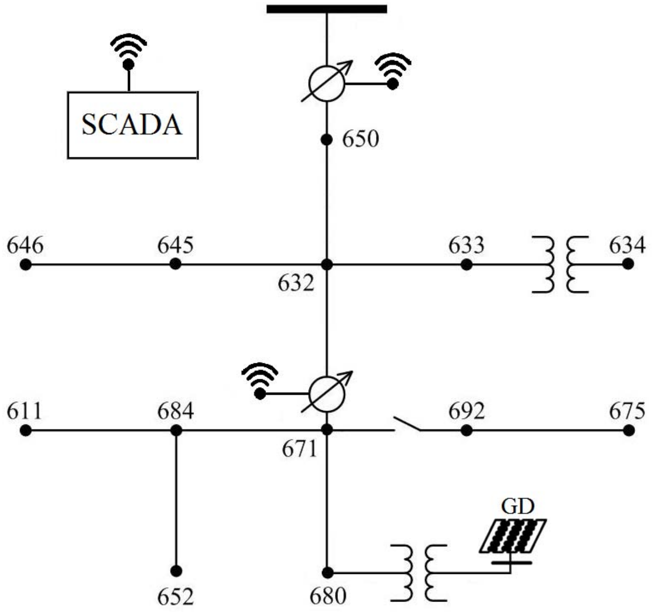


Fig. 5. Network Diagram.

There is two VR on this network that could receive commands from data acquisition and supervisory system (SCADA) and if necessary changes the Tap position regulating the output voltages.

The Simulink library provides a specific block called *Level-2 MATLAB S-Function* that can be utilized to implement the SCADA. This block is configured according to an external algorithm which defines the number of inputs, outputs and the relation of them. As shown in Fig. (6), were defined two main inputs and outputs ports. The first input gets the system time reference and the second receives voltage and Tap position data from regulators. The outputs are separated also by two, the first one is responsible to send the Tap command generated by the system and the second one sends all regulator data to be saved in an external memory bank.

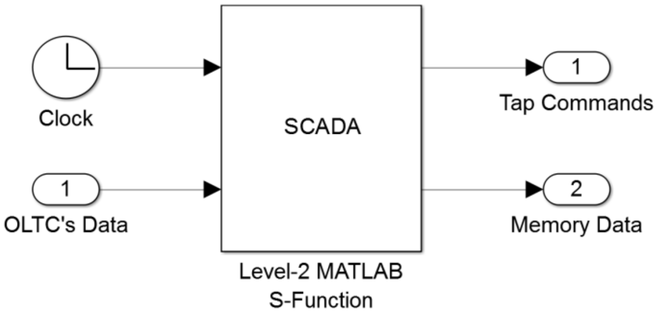


Fig.6. – Data Relation in SCADA System.

Receiving this data from each regulator, the SCADA analyzes if the voltage levels are within the insensibility range. This regulator insensibility was set as 2,5%, what means a voltage range from $0{,}975V_{ref}$ to $1{,}025V_{ref}$ acceptable by the system. At the moment that occurs the first voltage transgression, the system begins a count and still analyzing the voltage level to know if this is only a fast variation in the system due the dynamic load profile connected in the network or it is a real transgression. When the count hits a defined time, fixed as 18 seconds in the methodology, and the regulator still out of the acceptable range, the system predicts a new Tap position, utilizing the equation (5), that will set the voltage output as close as possible to the reference voltage. With the relation between Tap predicted and actual Tap position is generated a Tap change command that is sent to the regulator.

$$V_{out} = V_{in} \cdot [1 + (\Delta V_{TAP} \cdot N_{TAP})] \qquad (5)$$

Where, V_{out} is the output voltage, V_{in} is the input voltage, ΔV_{TAP} is the voltage variation for each switching, defined as $0{,}02\ V_{up}$, and N_{TAP} is the number of Tap changes needed to hit the new Tap position.

Fig. (7) shows the input and output voltage profile and their reaction due the switching commanded by the SCADA system. Fig. (8) shows the voltage regulator operation and his Tap switching.

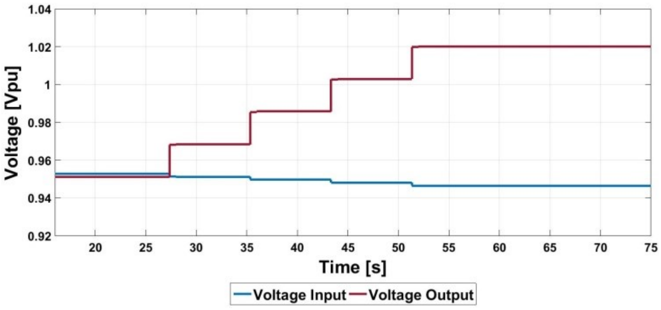


Fig. 7. – Voltage Regulator Analyzes .

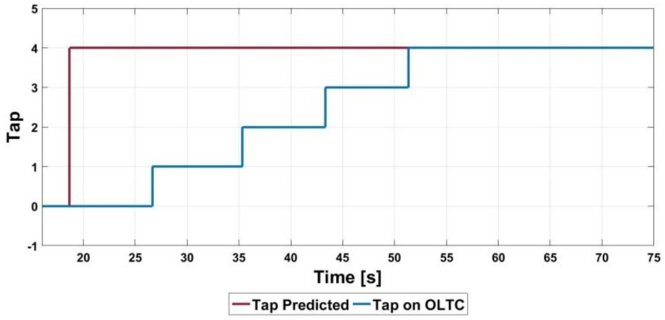


Fig.8. Regulator Tap Analyzes.

It is possible to see that with 0 as Tap position the regulator output voltage is above of the acceptable range. So, after 18 seconds from the first transgression detected by the SCADA, a new Tap position is predicted for this regulator according with his voltage reference, set as $1,02\,V_{up}$. Receiving this information, the VR stars the switching until hits the predicted Tap position.

The voltage regulator also presents a time delay to change his Tap. This delay can be variable or fixed. When utilized inverse temporization, the time delay depends the intensity of the voltage transgression. How in the present system was considered just a linear temporization, the delay time was fixed as 8 seconds for each Tap switching as shown in Fig.8.

V. CASE STUDY

For the analysis of the developed methodology, simulations with a test system were performed. This study considers a system compound of 2 identical feeders based on the IEEE 34 bus system, presented in Fig. 99, with the possibility of load transfer between both feeders.

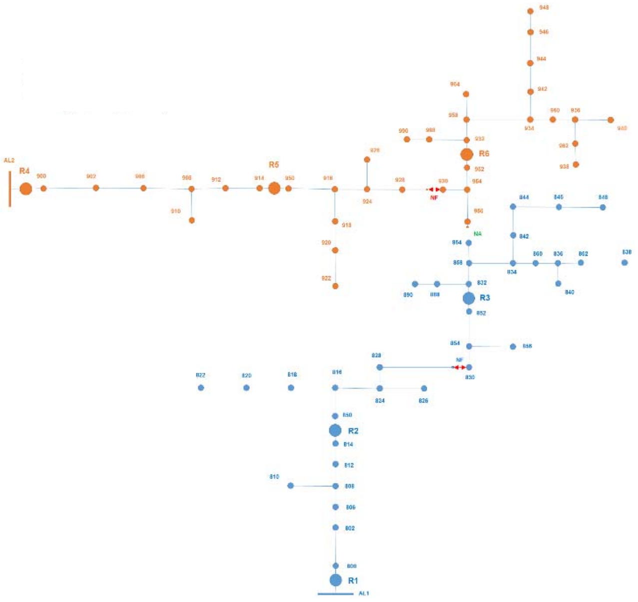


Fig. 9. Test Feeder.

For each analyzed scenario, two simulations were performed, one considering the normal operation of the voltage regulators and other applying the CDI-RT methodology, comparing the results obtained in terms of regularization time, number of switching and severity of transgression.

Fig. 10 illustrates the normal operation of voltage regulators, considering the transition between 19h to 20h.

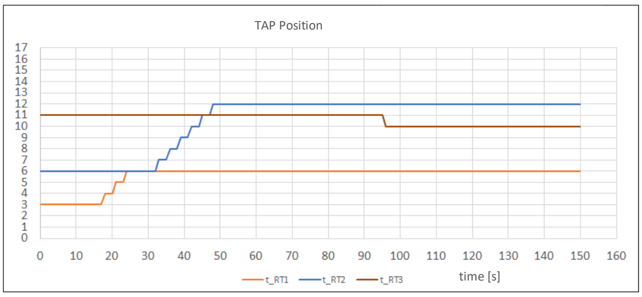


Fig. 10. TAP Set in Normal Operation.

The effect of these operations, associated with the influence of regulators to each other, results in output voltages shown in Fig. 11.

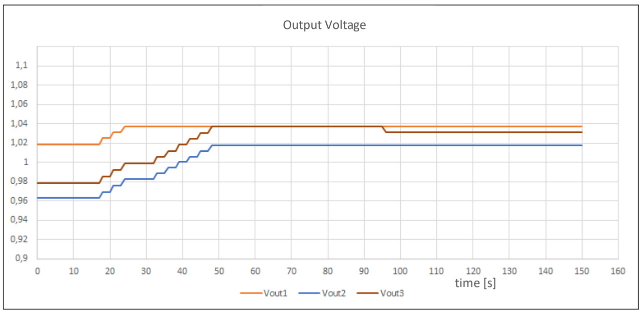


Fig.11. Output Voltage in Normal Operation.

It is observed that the timing adjustment is used to maintain operation sequence, starting it from the closer source regulators, leaving the farthest equipment to the end. However, when the source is regulated, the other regulators still needed some additional switches to get adjusted.

By using centralized control, the switching process is accelerated, making all regulators initiate their commutations. As can be seen Fig.12, the duration of the transgression was lower than in the previous condition. Additionally the number of switches was also reduced.

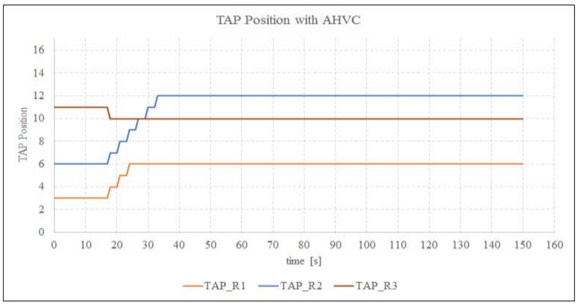


Fig.12. TAP Changing with CDI-RT.

In this configuration, the regularization occurs faster, resulting in the output voltages shown in Fig.13.

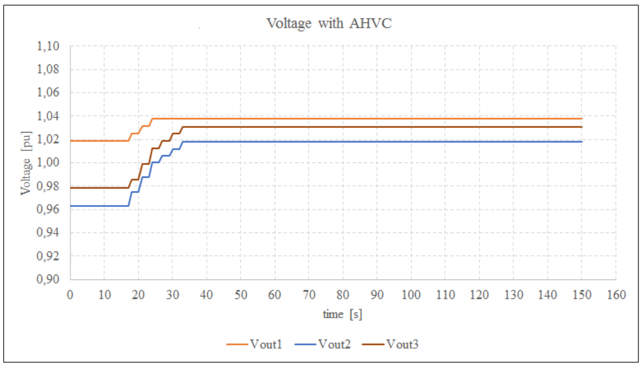


Fig.13. Voltage Output with CDI-RT.

Compared with the normal operation of voltage regulators, it is observed that, as seen in Table I, the severity of the transgression was reduced in all regulators.

Table I
Comparative between applied methods – Normal vs CDI-RT – Original Configuration

	Indicator	RT1	RT2	RT3
Normal	Switching Operations of SVR	3	6	1
	Severity Voltage Transgression Index [pu.s]	0,274	1,656	1,162
	Voltage Regularization [s]	24	48	96
CDI-RT	Switching Operations of SVR	3	6	1
	Severity Voltage Transgression Index [pu.s]	0,274	1,183	0,816
	Voltage Regularization [s]	24	33	18

For a better understanding of the severity index, Fig 14. shows a comparison between the normal operation and the CDI-RT operation on the RT3 regulator.

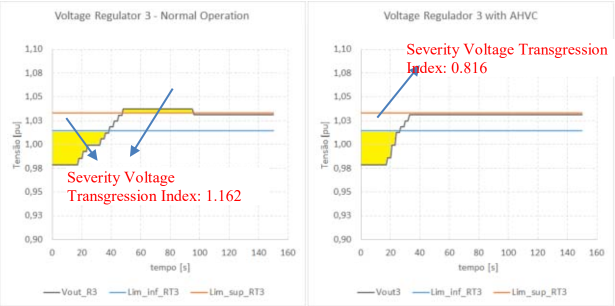


Fig.14. Severity Level –Normal Operation against CDI-RT.

CONCLUSION

This paper presents a methodology developed for dynamic setting changing of distribution voltage regulators under distributed generation presence or in reconfigurations that allows the quickly mode adjust of operation of the drivers for different operating conditions.

In a system with little ability to maneuver or charge transfer, the CDI-RT method, basically, operates in the improvement of voltage levels according to the seasonality of load and the different load levels that occur during the day. However for systems with more possibilities for transfer of loads between feeders, these configuration changes are perceived by the SCADA system, by monitoring key and the change in the load profile of the regulators. In these cases, the alarms send information to the setting and state estimation module, which update the network settings and the settings of regulators revalued.

Additionally the application of distributed controllers reduces the need for centralized control processing, enabling reduction of the need of processing related to the CDI-RT tools.

ACKNOWLEDGEMENTS

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