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VULNERABILITIES INTRODUCED BY THE INTERDEPENDENCIES BETWEEN ELECTRICAL GRID AND THE ICT SYSTEMS: DIAGNOSTIC INDICES FOR THE POWER GRID

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The European Commission declared in its Directive of October 20, 2004 "Critical Infrastructure Protection in the fight against terrorism", energy sector and information and communication technology (ICT) sector- critical infrastructure. As a result, research programs were started in order to detect and prevent various direct or indirect attacks, which could target the energy sector. In this paper, a software was developed for computing a diagnostic index, the voltage collapse index, which displays thru a message the state of the electric grid witch depends on the voltage level of the grid nodes.

Keywords: Voltage stability, voltage collapse, robustness index, critical infrastructure

1. Introduction

During recent past years, numerous incidents have been reported especially because of voltage instability. Old electrical networks and the opposition of the environmental protection groups to build new power lines caused the voltage instability limits to be increasingly important in terms of a secure operation of power system. All this has led to the need of better understanding the phenomenon of voltage stability, to be able to detect it and by developing new ways to succeed in reducing incidents that occur because of this.

The transmission of electricity requires a large and transparent electricity infrastructure, made of transmission lines, stations, and generators. These components cannot work without the assistance of a vast cache of information infrastructure, lines of communication and without a control center. The vast expansion of the information infrastructure in recent years has brought significant savings and reliability improvements [5]. The most important economic perspective is the ability to operate with smaller limits of certainty, because the operator can access more accurate information about power system status and it also has the possibility of very fast response for disturbances helped by lots of real

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time diagnostic indices ([1], [2]). The informational infrastructure contributes evenly for the security of the system, by alerting the operator about undesired events, and by the possibility of providing desired corrective action. The study and simulation applications are focused on the vulnerability of power networks, their ability to deal with the spread of major power outages.

The voltage stability can be investigated with the traditional methods, because the voltage collapse is a relatively slow process, by using the static analysis, considered as a small signal phenomenon [4]. The dynamic phenomenon of voltage collapse was analyzed with various proposed analytical tools: Q-V curve, singular value, P-V curve, eigenvalues, sensitivity etc. The big problem is that they are methods of slow and intensive calculation, making them less viable for a real-time calculation, where the operator of the control center needs to take actions in very short time to prevent a voltage collapse.

This paper is just a little part of a bigger research program made at the Polytechnic National Institute of Grenoble, in witch more robustness indices were proposed. For this paper a method for calculating one of these indices witch compose the robustness index, voltage collapse index has been developed, considering as constant the generator voltages, in amplitude and phase. The index should have the possibility to follow the state of the system, and to show to the dispatcher, the system tends to a critical situation, with a very fast computation.

For the simulation of the dynamic events it was used an IEEE nine-bus system, from the library of the used software: PSAT.

2. Modeling of voltage collapse index

The index witch predicts, with sufficient accuracy, the voltage problem is derived from the basic static power and Kirchhoff's law [3].

To better understand the considered steps taken in order to determine the voltage collapse index, a simple circuit is presented below, circuit made by bus 1, the generator, and bus 2, a load bus whose behavior will be investigated (Fig. 1), [1].

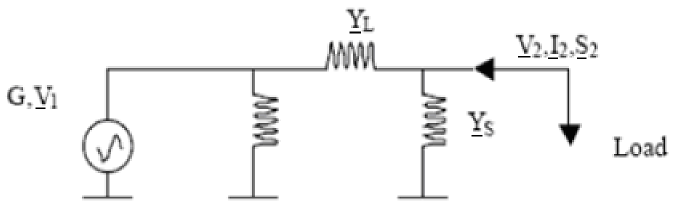

Fig. 1. The single generator and load system

From the following equations (1), (2), (3), (4) the simple system is described (where the line under a letter represents a vector, * indicates the complex conjugate of the vector):

$$\underline{I}_2 = \underline{V}_2 \underline{Y}_s + \left(\underline{V}_2 - \underline{V}_1 \right) \underline{Y}_L = \frac{\overset{*}{\underline{S}_2}}{\overset{*}{\underline{V}_2}} \tag{1}$$

$$\overset{*}{\underline{S}}_2 = V_2^2 \underline{Y}_s + V_2^2 \underline{Y}_L - \overset{*}{\underline{V}}_2 \underline{V}_1 \underline{Y}_L = V_2^2 \underline{Y}_{22} + \underline{V}_0 \overset{*}{\underline{V}}_2 \underline{Y}_{22} \tag{2}$$

$$\underline{Y}_{22} = \underline{Y}_s + \underline{Y}_L \tag{3}$$

$$\underline{V}_0 = -\frac{\underline{Y}_L}{\underline{Y}_L + \underline{Y}_s} \underline{V}_1 \tag{4}$$

Because the reactive problem is the problem of the voltage stability, the buses of the circuit are classified in two categories: Generator bus (PV bus and Slack bus) and Load bus (PQ bus), where the generator provide the reactive power that the system need to keep the magnitude of the voltage.

The Kirchhoff's law is represented with the equation (5):

$$\underline{I}_{system} = \begin{bmatrix} \underline{I}_L \\ \underline{I}_G \end{bmatrix} = \begin{bmatrix} \underline{Y}_{LL} & \underline{Y}_{LG} \\ \underline{Y}_{GL} & \underline{Y}_{GG} \end{bmatrix} \begin{bmatrix} \underline{V}_L \\ \underline{V}_G \end{bmatrix} = \underline{Y}_{system} \underline{V}_{system} \tag{5}$$

where the subscript L means load bus, and G means generator bus.

From equation (5), with a few artificial calculations it results the hybrid matrix shown in equation (6):

$$\underline{Z}_{LL} = \underline{Y}_{LL}^{-1}$$

$$\begin{bmatrix} \underline{V}_L \\ \underline{I}_G \end{bmatrix} = \begin{bmatrix} \underline{Z}_{LL} & -\underline{Z}_{LL} \underline{Y}_{LG} \\ \underline{Y}_{GL} \underline{Z}_{LL} & \underline{Y}_{GG} - \underline{Y}_{GL} \underline{Z}_{LL} \underline{Y}_{LG} \end{bmatrix} \begin{bmatrix} \underline{I}_L \\ \underline{V}_G \end{bmatrix},$$

then

$$\begin{bmatrix} \underline{V}_L \\ \underline{I}_G \end{bmatrix} = \begin{bmatrix} \underline{Z}_{LL} & F_{LG} \\ K_{GL} & \underline{Y}_{GG} \end{bmatrix} \begin{bmatrix} \underline{I}_L \\ \underline{V}_G \end{bmatrix} = [\underline{H}] \begin{bmatrix} \underline{I}_L \\ \underline{V}_G \end{bmatrix} \tag{6}$$

$\underline{V}_L$, $\underline{I}_L$ - are the voltage and current vectors at the load buses
$\underline{V}_G$, $\underline{I}_G$ - are the voltage and current vectors at the generator buses
$\underline{Z}_{LL}$, F_{LG}, K_{GL}, $\underline{Y}_{GG}$ - are the sub-matrices of the hybrid matrix H.

The voltage of the all load bus is represented in equation (7), from the Kirchhoff's system (5), which can also be expressed like equation (8), from where we can extract the substituting equivalent V_{0j} , S_j' and Y_{jj}'.

$$\overset{*}{\underline{V}}_j = \sum_{j \in L} \underline{Z}_{ij} \overset{*}{\underline{I}}_j + \sum_{i \in G} A_{ji} \overset{*}{\underline{V}}_i \tag{7}$$

$$A_{ji} = -\underline{Z}_{LL} \underline{Y}_{LG} = -F_{ji}$$

$$\underline{V}_j^2 + \underline{V}_{0j} \overset{*}{\underline{V}}_j = \frac{\overset{*}{\underline{S}}_j}{\underline{Y}'_{jj}} \tag{8}$$

where:
$$\underline{V}_{0j} = -\sum_{i \in G} A_{ji} \underline{V}_i \tag{9}$$

$$\underline{Y}'_{jj} = \frac{1}{\underline{Z}_{jj}} \tag{10}$$

$$\overset{*}{\underline{S}}{}'_j = \left(\sum_{\substack{j \in L \\ i \neq j}} \frac{\underline{Z}_{ij} \overset{*}{\underline{S}}_j}{\underline{Z}_{ii} \overset{*}{\underline{V}}_j} \right) \underline{V}_i \tag{11}$$

With these entire equivalents [6], the voltage stability indicator for the load L_j can be obtained with the equation (12), and for the system with equation (13).

$$L_j = \left| 1 + \frac{\underline{V}_{0j}}{\underline{V}_j} \right| \tag{12}$$

$$L_{system} = \underset{j \in L}{Max} \left(L_j \right) \tag{13}$$

After the indicator L result, the two thresholds TH_1 and TH_2 are calculated (eq. (14)):

$$\begin{cases} \text{TH1=1,02*L} \\ \text{TH2= L} \end{cases} \tag{14}$$

and with this result, the robustness index, composed by the following indicators (eq. (15)):

$$\text{(RI)= max}\{\text{(SSS);(SPIR);(VCI);(FD);(LS);(RTM)}\}, \tag{15}$$

where if we suppose the (SSS)=0, (FD)=0, (SPIR)=0, (LS)=0, (RTM)=0,
the robustness index will be:

$$\text{(RI)= max}\{\text{(VCI)}\} \tag{16}$$

calculated in relation with voltage collapse index (eq. (17))

$$(VCI)=\begin{cases}\text{3 si VCI}_1\text{<TH2}\\ \text{2 si VCI}_1\text{<TH1}\\ \text{0 if another event}\end{cases}, \tag{17}$$

and the display, from the control center, will show one of the following message: normal, alert, action or danger (eq.(18)).

$$(RI)=\begin{cases}3\Rightarrow\ \text{Danger}\\ 2\Rightarrow\ \text{Action}\\ 1\Rightarrow\ \text{Alert}\\ 0\Rightarrow\ \text{Normal}\end{cases} \tag{18}$$

The messages have the following significations:

- **Normal** when the answer of the robustness index is 0, the comportment of the system is good and stable.
- **Alert** when the answer of the robustness index is 1, the comportment of the system show that something is happening, what may have consequences or not, but the operator must increase the attention.
- **Action** when the answer of the robustness index is 2, the comportment of the system is not very stable, he may be at risk, the operator may take actions to stabilize the system.
- **Danger** when the answer of the robustness index is 3, the level of the risk in the system is very high, it is possible that the operator do not have very much time to take actions.

After the dispatcher operator saw the message, he has to take measures to eliminate the problems, if any.

The all algorithm of the simulation is shown in the Fig. 2. It is based on a method [5], [6], [7] which effectiveness has been proved by industrial usage. For this project the imposed decisive selection criterion was robustness. Despite the fact that more recent approaches are based on meta-heuristic methods (neural networks and genetic algorithms), the choice was made to use a heuristic approach.

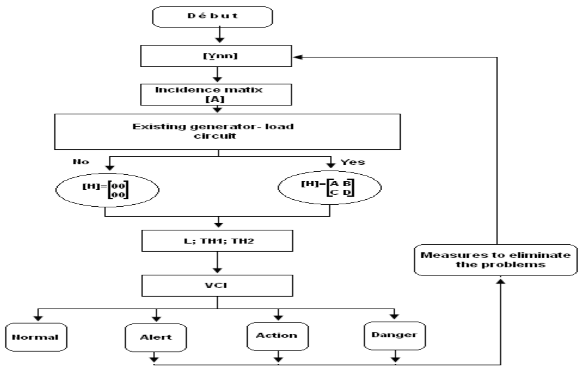

Fig. 2. The algorithm of the simulations

3. The simulations and the results

The test scheme used for the simulation is the IEEE nine-bus as shown in Fig. 3.

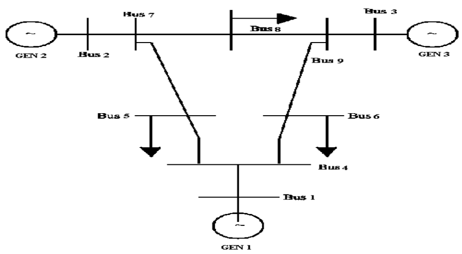

Fig. 3. Simulation test case IEEE nine-bus system.

The simulations were made for more scenarios; here the scenario most representative results will be presented. The scheme has tree type of consumers, the consumer from bus 5 is charged at 125+j50 MVA, the consumer from bus 6 is charged at 90+j30 MVA and the consumer from bus 8 is charged at 100+j35 MVA.

When the contingency happens, in this scenario case, after the trigger of two lines and the loss of a generator (Gen 3), the voltage and the reactive power are oscillating, the voltage collapse index takes different values and the computer program shows the state of the system after the contingency, in relation with the voltage level (Fig. 4.).

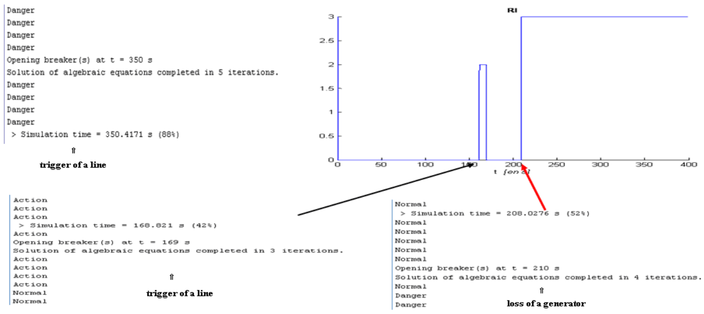

Fig. 4. Fragments of the status of the system show from the program to the display

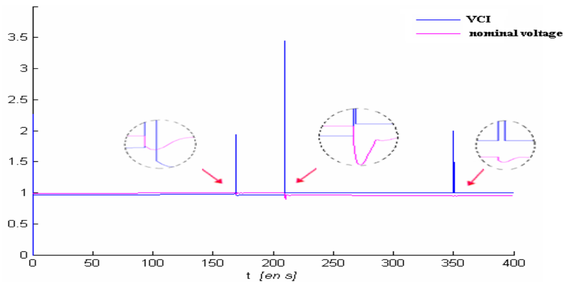

Fig. 5. The VCI representation in relation with the nominal voltage during and after the contingency

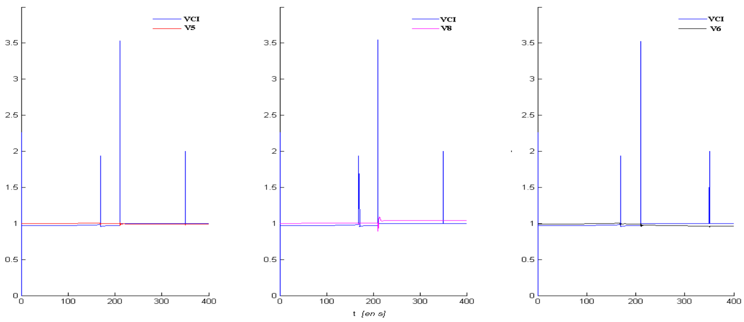

Fig. 6. The voltage variation in each bus during and after the contingency

In the presented curves illustrate the voltage collapse index increases during the contingency (Fig. 5.); if its value after the contingency is higher than the nominal voltage value, the system is in voltage collapse (Fig. 6.).

6. Conclusions

The purpose of this paper was to make a computer program witch can monitor the operation of power system, witch we want to be safe and to ensure normal operating parameters (in our case the buses voltage) in real time.

One of the most important parameters of a power system is the voltage, and the control center operator should ensure voltage stability in any situation that arises.

For it, in this paper a computer program was made in order to help the dispatcher to monitor the system status at any moment of time.

As seen from the result of the simulation, with different scenarios, when there is a contingency, such as a trigger line or loss of a generator, according to the scheme that results from the test system, the operator receives a message that announces the system state and the severity of the event in relation to the voltage in the consumer nodes, during and after the event.

We can see that we succeed to follow the purpose: to monitor the system operating with dynamic state.

In the future, we want to make the validation of the developed computer program, through the Eurostag software, the most used in France by the enterprises.

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