Analysis of the Impact of New Power Sources to Voltage Sags Using Zbus

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***Abstract*— This paper presents a methodology for voltage sags magnitudes calculation in the presence of alternative energy sources and/or distributed generators. The method determines the degree of influence of the parameters from the new generating units connected to the electrical system with regard to voltage sags magnitudes. The impedance matrix – *Zbus* is used to obtain analytical expressions that represent key variables in the analysis of voltage sags caused by faults in the grid. The methodology is applicable to any network topology, from transmission to distribution and seems to be a very promising tool to estimate voltage sags in smart grids.**

***Keywords*-Alternative Sources, Distributed Generation, Faults, Impedance Matrix, Voltage Sags.**

I. INTRODUCTION

The use of generators in the distribution network has the advantage of reducing the electrical losses and delay the need to extensively expand the transmission system, since the generators are located near the loads on the distribution system [1]. Alternative energy sources generally bring similar benefits and the impact analysis of the insertion of these sources to the power quality becomes relevant in this context.

In [2] several distributed generation topologies were simulated using EMTDC/PSCAD. Four cases are analyzed to lead to independent results, focusing on aspects such as location, types and methods of control of the generating units, fault position and variation of the generators' output power.

A study to make a comparison between the utilization of synchronous machines and inverters is developed in [3]. The negative influence of distributed generation units acting in the voltage regulation in systems operating in fault conditions was also cited.

In [5] there are important considerations on the modeling of typical elements of an electric power system with a view to the bus impedance matrix. The impedance matrix is used in [6] for fault current studies in systems with distributed generation. This matrix is cited because it takes into account all elements of the system: transmission grid, subtransmission grid, the primary distribution grid, and any generators that appear in the system.

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Thus, it is possible to suggest a study focused on parameters of distributed generators throughout the grid or of alternative sources in a general manner. Typically we found methods of analysis of voltage sags based on simulations [2] however, the conclusions are extracted by comparing a series of simulation results, which is a not predictive method of analysis. In this way, if we do not perform other simulations, we are not able to draw a conclusion.

We can check that although it is possible to extract the results of a series of simulations, there is not an analytical expression for the voltage monitoring points yet. An analytical expression gives the study a predictive character.

In this context, it is proposed in this paper an analytical approach to the analysis of the generating units' influence in the magnitudes of voltage sags due to faults only, overload conditions are not regarded. The method of calculating the magnitudes of voltage sags is based on the use of the impedance bus matrix (*Zbus*).

II. METHODOLOGY PROPOSED

The *Zbus* matrix brings important information about the analyzed power grid, especially for fault calculations. The influence of the impedance of the generators and transformers on the system behavior is analyzed in [4] as regards faults. The modeling is done using the bus impedance matrix built by direct methods, generators' parameters enter according to the Norton equivalent and the other elements are added by modifying the matrix initially built.

An analysis of faults in large power systems becomes more feasible when using a direct building method for *Zbus*, since admittance matrix (*Ybus*) inversion can become a problem, in the case of this matrix being ill-conditioned or very sparse (radial distribution). Moreover, obtaining a literal expression, depending on the parameters of the distributed generators, is almost unfeasible due to the complexity of matrix inversion algorithms in large systems.

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A. *Building and Changing Zbus Elements*

Initially a direct impedance bus building algorithm was implemented in Matlab, as shown in [7] and [8]. In this method, the matrix is mounted in a step-by-step way. A ground is taken as the reference bus; after that, the new buses are connected to it and, finally, the connections between the existing buses are added; Kron reduction is used in this process. A detailed analysis of the Kron reduction from the perspective of graph theory is performed in [9], given its importance in the study of electrical networks. In the program, the circuit connections are described as Matlab vectors containing bus indexes and the p.u. values of shunts and series impedances.

Regarding the elements of the system, we consider a constant impedance model for the loads, the classical π model for the lines and a linear model for the transformers, these models are satisfactory when the cause of sags are faults [5].

Thus, alternative sources are connected in parallel to one or more system buses, so the use of the Norton equivalent [4] becomes suitable. The subtransient reactance of the generator must be used, because the study refers initially to short circuits and later to voltage sags. The use of the smallest generator reactance makes the calculation more conservative since the largest value of the currents is assumed during the fault period; valid for both synchronous generators and for the induction generators [10].

Concerning smart grids, the alternative generators are located in the distribution level. Hence, we have to pay attention to the extensive use of frequency inverters in the connection of these generators (photo voltaic and wind generators). The impedance model of a frequency inverter brings some difficulties due to its nonlinearity [11] and its value changes according to the used control method [12].

B. *Other Generators Influence*

In the developed program, symbolic variables can be assigned to the parameters of a given generator (subtransient reactance). The equivalent shunt impedance at a particular bus containing the generator is calculated as a function of the generator reactance and this result is used as an input for the impedance matrix construction algorithm described [8].

To short-circuit studies in a given bus k, one may use equation (1) for calculating the fault current $I_f(x)$, where V_{pref} is the pre-fault voltage, Z_f is the fault impedance and $Z_{kk} = Z_{kk}(x)$ is the self-impedance of bus k taken from (2), being x, the value of the generator's fault reactance. All the elements of (2) are dependent on x, which allows checking how the parameter x of a generic generator influences *Zbus*.

$$I_f = \frac{V_k^{pref}}{Z_{kk}+Z_f} \quad (1)$$

$$Z_{bus}(x) = \begin{bmatrix} Z_{11}(x) & \cdots & Z_{1n}(x) \\ \vdots & \ddots & \vdots \\ Z_{n1}(x) & \cdots & Z_{nn}(x) \end{bmatrix} \quad (2)$$

A traditional method of calculating the voltage sags magnitudes during faults is given by (3), according to [7].

$$V_{sag}(x) = \begin{pmatrix} V_1(x) \\ \vdots \\ V_n(x) \end{pmatrix} = \begin{pmatrix} V_1 \\ \vdots \\ V_n \end{pmatrix}^{pref} - \begin{bmatrix} Z_{11}(x) & \cdots & Z_{1n}(x) \\ \vdots & \ddots & \vdots \\ Z_{n1}(x) & \cdots & Z_{nn}(x) \end{bmatrix} \cdot \begin{pmatrix} 0 \\ I_f(x) \\ 0 \end{pmatrix} \quad (3)$$

In this calculation, the system operating condition in pre-fault (approximation to the load flow) considers all voltages close to 1 p.u. and neglects load currents.

In this way we obtain the expression for *Vsag (x)* in all buses for a given point of fault occurrence. This allows observing the *Vsag* behavior in any bus to a range of values that the reactance x of the generator can assume. The flowchart shown in Fig. 1 summarizes the proposed methodology.

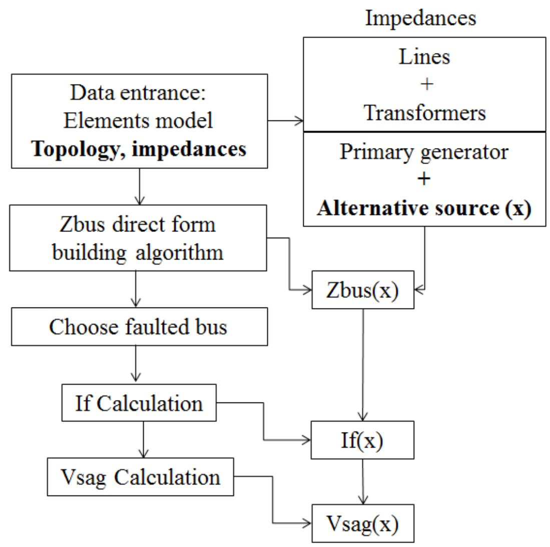

Fig. 1. Method Flowchart.

III. CASE STUDY

In order to illustrate the methodology described in II, let us consider an original 4 bus transmission system to which is connected a synchronous generator (alternative source) through a transformer [13], as shown in Fig. 2.

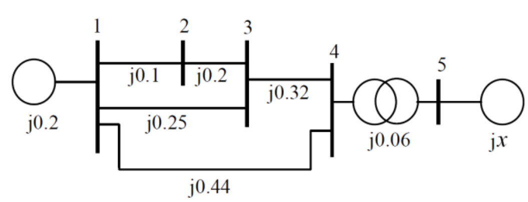

Fig. 2. Test Circuit.

All impedances in the circuit are in p.u. and the operating condition is 1 p.u. voltage in all buses (flat-start condition). The loads can be neglected for short circuit studies, due to its low influence. The generators' fault impedances are treated as constant minimal values. This leads the research to the worst case analysis, because higher current levels are assumed.

A fault at the bus 3 with $Z_f=0$ was simulated using the program developed in Matlab. The Fig. 3 shows the impedance matrix obtained with all its elements expressed as a function of x (generator subtransient reactance).

$$\begin{bmatrix} Z_{11}(x) & Z_{12}(x) & \frac{(24650x+5351)j}{5(24650x+11931)} & Z_{14}(x) & Z_{15}(x) \\ Z_{21}(x) & Z_{22}(x) & \frac{28(1050x+247)j}{5(24650x+11931)} & Z_{24}(x) & Z_{25}(x) \\ Z_{31}(x) & Z_{32}(x) & \frac{2(19450x+5023)j}{5(24650x+11931)} & Z_{34}(x) & Z_{35}(x) \\ Z_{41}(x) & Z_{42}(x) & \frac{658(50x+3)j}{5(24650x+11931)} & Z_{44}(x) & Z_{45}(x) \\ Z_{51}(x) & Z_{52}(x) & \frac{6580xj}{(24650x+11931)} & Z_{54}(x) & Z_{55}(x) \end{bmatrix}$$

Fig. 3. *Zbus(x).*

The impedance bus matrix elements obtained can be useful in the protection systems parameterization, as in distance relays [14], since they stand for the Thevenin equivalent impedance view up to a given point of the grid, which can be set by the program.

The k-column of Fig. 3 has all data necessary for the short-circuit analysis, pre-fault load currents are neglected. As the fault is at bus 3, implies $k=3$. Expressions for the fault current $I_f(x)$ (4) and the voltage sag magnitude in each bus $V_{sag}(x)$ (5) as functions of the new generator reactance (x) were obtained by using equations (1) and (3).

$$I_f(x) = -\frac{5412050j}{389(19450x+5023)} - \frac{2465j}{778} \quad (4)$$

$$V_{sag}(x) = \begin{pmatrix} \frac{197400}{389(19450x+5023)} + \frac{285}{778} \\ \frac{131600}{389(19450x+5023)} + \frac{95}{389} \\ 0 \\ \frac{1268624}{389(19450x+5023)} + \frac{60}{389} \\ \frac{1652567}{389(19450x+5023)} + \frac{60}{389} \end{pmatrix} \quad (5)$$

A mathematical analysis of fault current (4) and voltage sags magnitudes vector (5) allows us to set limits within which the values of the magnitudes of I_f and V_{sag} vary. Thus, we can calculate the upper and lower limits for the fault current I_h (6) and I_l (7), as well as for voltage sags, obtaining V_{sagh} (8) and V_{sagl} (9).

$$I_h = |\lim_{x\to 0} I_f(x)| = |-\frac{5412050j}{389*(5023)} - \frac{2465j}{778}| = 5.9382 \text{ pu} \quad (6)$$

$$I_l = |\lim_{x\to\infty} I_f(x)| = |-\frac{2465j}{778}| = 3.1684 \text{ pu} \quad (7)$$

$$V_{sagh} = \lim_{x\to 0} V_{sag}(x) = \begin{pmatrix} 0.4674 \\ 0.3116 \\ 0.0000 \\ 0.8035 \\ 1.0000 \end{pmatrix} \quad (8)$$

$$V_{sagl} = \lim_{x\to\infty} V_{sag}(x) = \begin{pmatrix} 0.3663 \\ 0.2442 \\ 0.0000 \\ 0.1542 \\ 0.1542 \end{pmatrix} \quad (9)$$

By the analysis of (6) e (7) we can observe that the values obtained for the lower limit of the short-circuit current I_l correspond to the ones with the new generator disconnected, confirming the idea that the inclusion of new generators over the grid increases the level of short-circuit current.

Concerning V_{sagl} (9), and taking into account the Fig. 4, it is observed that the lowest possible voltage sag magnitude is when the new generator is not connected to the grid (infinite reactance). Thus, the addition of a generator to the original system promotes a less severe sag than that recorded without its presence (regardless of its reactance), although the value of fault current registers an increase.

TABLE I shows some obtained values of I_f and V_{sag} for a variation of the generator reactance found in practical applications, all values are in p.u.

TABLE I. RESULTS – FAULT AT BUS 3

Reactance (x) (pu)	I_f (pu)	$V_{sag}(1)$ (pu)	$V_{sag}(2)$ (pu)	$V_{sag}(4)$ (pu)	$V_{sag}(5)$ (pu)
0.05	5.4889	0.4510	0.3006	0.6892	0.8628
0.10	5.1650	0.4392	0.2928	0.6223	0.7639
0.15	4.9205	0.4302	0.2868	0.5650	0.6893
0.20	4.7293	0.4233	0.2822	0.5201	0.6309
0.25	4.5758	0.4177	0.2784	0.4841	0.5840
0.30	4.4497	0.4131	0.2754	0.4546	0.5455
0.35	4.3444	0.4092	0.2728	0.4299	0.5133
0.40	4.2551	0.4060	0.2706	0.4090	0.4861

Fig. 4 shows the curves related to the modulus of fault current and voltage sags magnitudes on the buses for a range of reactance values higher than shown in Table I, in this case, 140 different values of x were taken, starting at 0.05 up to 7 p.u. with a step of 0.05 p.u.

The use of analytical approach dependent on the fault reactance x for voltage sags assessment increases the level of predictability and controllability of the system.

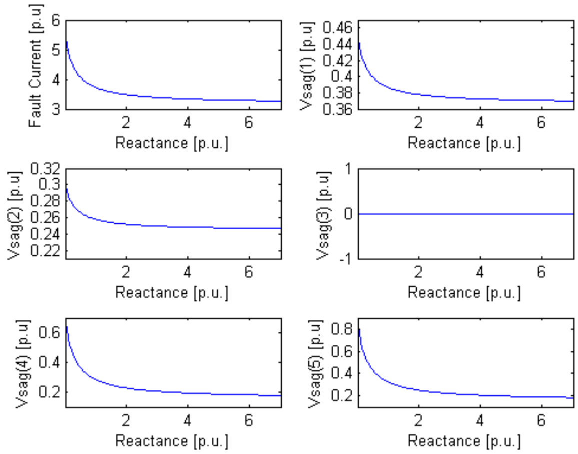

Fig. 4. $I_f(x)$ and $V_{sag}(x)$.

According to Fig. 4, the inverse relation between fault current and fault impedance *x* of the generator becomes explicit. The voltage at bus 3 is zero due to being the faulted point. The voltages at other buses have their behaviors set by the position of the new power source as well as the connections and fault location.

We can notice the derivatives in regard to *x* decreasing at each point; this value tends to zero for generator disconnection, which is a feasible result.

Moreover, it is possible to divide the "*x*-axis" in continuous gaps of reactance values and include a given type of generator at a certain operation mode into a group, given the impedance variations caused by these factors.

Other topologies can be simulated, but the results will not necessarily follow this case study, even though this analysis shows the program capability to estimate voltage sags without performing a lot of simulations.

IV. CONCLUSIONS

According to the proposed methodology the values of the voltage sags magnitudes vector were obtained. These values were calculated taking into account the several types of generators that can be connected to the system, since the reactance of the generator has inherent variations depending on the type (synchronous or induction machine) as well as the size and power of the generator.

Furthermore, the reactance might be abstracted as the impedance presented to the generator interface to the grid in the case of frequency inverters, leaving the problem of modeling the inverters impedance in background.

The mathematical analysis of the obtained expressions allowed us to have a real sense of the range of values that each interest variable can assume in case of a fault at any point of the grid.

The single simulation performed by the program presented a simplification over traditional evaluation methods to analyze issues related to voltage sags caused by faults.

The capability of the proposed methodology at obtaining voltage sags equations was observed taking into account the growing number of connections come from new power sources coupling to already operating electrical networks.

A more sophisticated model can be developed in order to study voltage sags mitigating techniques using power electronics devices. Moreover, the monitoring of the impedance changes assigned by an external variable may be useful in relays parametrization related to smart grids.

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