POWER QUALITY DEGRADATION CAUSED BY CONGESTED TRANSMISSION SYSTEM AND DYNAMIC LOADS.

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ABSTRACT

This paper shows how excessive loading on the bulk transmission system may lead to a degradation of the power quality provided to consumers with sensitive loads, by enlarging the vulnerability areas associated with these loads. A simple two busses system is used to derive equations that easily express the increasing sensitivity of receive-end voltage to power deviations that may occur due to system disturbances, for instance. The conclusions of this simplified analysis are extended and validated considering an actual system with similar short circuit power, with simulation and monitoring results.

The phenomenon of "Delayed Recovery Voltage", that may occur when a weak system supplies a large amount of motor load, such as air conditioner, is also covered. In such situations, a voltage sag to values below 70 % may cause a "stall" in the air conditioner motors that drive the compressors.

This phenomenon will be aggravated when long times of fault clearing are of concern. The recording of actual case of the Delayed Recovery Voltage phenomenon, collected by monitoring devices installed in the system is presented in this paper.

INTRODUCTION

To be competitive in a worldwide global market, many of the industrial plants have been modernized with an intensive use of robots, computers and several complex microprocessor systems that control most of the industrial processes. This is a strong and irreversible trend to produce competitive products; that is, maximizing quality and minimizing costs. Unfortunately, due the extremely high sensitivity of these modern devices, equipment and systems – DES, to temporary voltage variations, caused by faults on transmission and distribution systems, an excessive incidence of interruption on industrial processes have been verified in last years throughout Brazil regions. This is especially important for long lines, weak and predominant radial transmission systems supplying sensitive load at the receiving end. Due the radial configuration, almost all of the bulk transmission system is contained within the vulnerability area associated to the sensitive load at the end of the system. Also, due the long distances of the transmission lines, the expected fault incidence may be relatively high. Figure 1 shows a typical structure of a bulk high voltage transmission system that supplies several subsystems or distribution systems with middle voltage levels. It is obvious that faults anywhere in the transmission system will dramatically affect the sensitive load located at the receiving end. Therefore, the construction of additional transmission lines in parallel with the already existing lines will increase the total length of the lines exposed to faults, so that the incidence of voltage sags on the sensitive load should increase.

On the other hand, the magnitude of voltage sags on the sensitive load (Fig.1) caused by faults on subsystems A and C will depend on the stiffness (level of short circuit power) of the bulk system bus from which A and C are supplied.

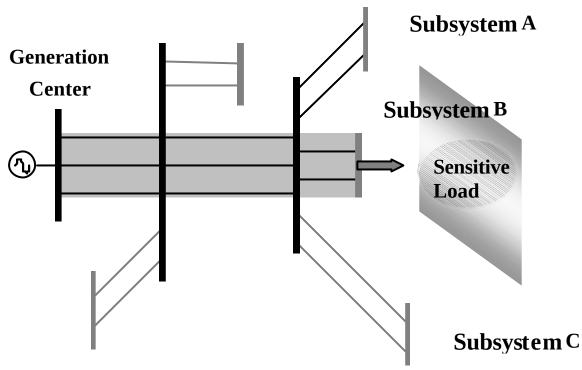

Figure 1 – Typical configuration of a radial transmission system supplying distribution systems

In other words, the magnitude of voltage sags sensed by the load and, as a result, the number of load interruption due to faults on subsystems A and C will be reduced when additional lines are incorporated to the transmission system. Therefore, when new lines are added to the transmission system, a higher incidence of faults on the transmission system is likely to occur. However, voltage sags caused by faults on the subsystem become less severe. Thus, the number of interruptions of the sensitive load may be higher or lower. The resulting predominant effect of such opposite factors of influence will depend on the relative values of the fault incidence rate (number of faults per year per km) on the transmission system and on the subsystem. However, in actual systems, the fault incidence rate on middle (88kV, 69kV) and distribution (13.8kV) voltage levels are usually higher than this parameter on the high voltage transmission systems (230kV and above). This is the case of the system considered hereunder, for which the faults on the subsystems are the main focus of our analysis.

FUNDAMENTAL CONCEPTS

Steady state voltage control, equipment loading, reactive power dispatch are examples of load flow studies. These studies usually consider the electric system operating under extreme heavy and light load conditions so that the means of voltage control are capable of providing the required system voltage profile.

Although these load flow studies consider the electric system as being on the "steady state" condition, strictly speaking, the voltages on actual systems are continuously changing as a result of the normal load variations, equipment switching, etc. Even the faults occurring in remote locations, at the distribution voltage level can be seen, at the system high voltage busses, as variations of the active and reactive power delivered to the respective feeder. The ability of the system to preserve a voltage profile immune (or within the tolerable range) to the mentioned normal "disturbances" is an important attribute for radial and weak systems. This attribute, usually referred to as "system stiffness", is closely related to the system short circuit power and may be regarded as a parameter that reflects how much the transmission system voltage is affected by faults on distribution.

The paper demonstrates that the vulnerability area of a sensitive load to subsystem faults is enlarged due to the heavy loading of the transmission system, comprised by two 230 kV transmission lines. In this case, the system "stiffness" depends not only on system short-circuit power but also on transmission system loading

A. *Analytical Analysis for a Simple System*

Let's consider the simple system shown on Figure 2.

The simplest way to express the change on voltage magnitude due to a small variation on the reactive power delivered from the bus is:

$$\Delta V_2 = -X.\Delta Q = -\frac{1}{S_{CC}}.\Delta Q \qquad (1)$$

where the variables are expressed in "pu" and S_{CC} is the short circuit power on bus 2 and X is the equivalent series reactance after the elimination of the shunt capacitive admittance using Thevénin's theorem.

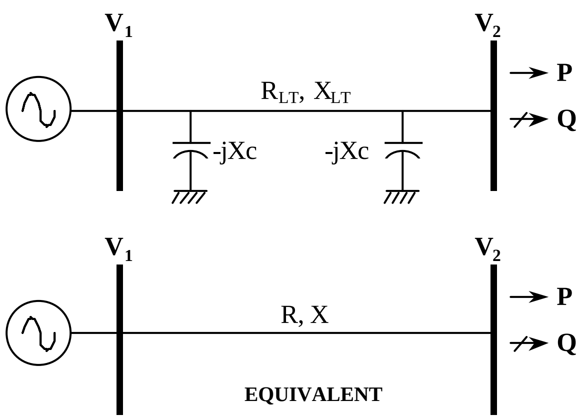

Figure 2 – Simple two busses system

When the influence of the active power variation has to be considered, the above equation becomes:

$$\Delta V_2 = -\frac{1}{S_{CC}}.\Delta Q - \frac{R}{X}\frac{1}{S_{CC}}\Delta P \qquad (2)$$

where the variables are also expressed in "pu" and R is the equivalent series resistance.

Equation 2 indicates that the voltage variation on bus 2 only depends on the system short circuit power. In fact, this equation is applicable when the system is operating at no load or at light load conditions. As the system loading increases, a more detailed expression must be used:

$$\Delta V_2 = \frac{\partial V_2}{\partial Q}\Delta Q + \frac{\partial V_2}{\partial P}\Delta P \qquad (3)$$

where:

$$\frac{\partial V_2}{\partial Q} = -\frac{Q(R^2+X^2)+XV_2^2}{[2(RP+XQ)-V^2+2V_2^2]V_2} \quad (4)$$

$$\frac{\partial V_2}{\partial P} = -\frac{P(R^2+X^2)+RV_2^2}{[2(RP+XQ)-V^2+2V_2^2]V_2} \quad (5)$$

By making P=Q=0 in equations (4) and (5), equation (3) becomes equation (2).

Figure 3 shows how the above parameters change with the system loading for a constant unit power factor. This is the case of a 230kV, 230km transmission line, 1 cable per phase, the parameters of which on 100MVA base are:

R_{LT}=4% ; X_{LT}=22%, B_{LT}=36%(X_C=5.56pu).

By using the equivalent circuit parameters to eliminate the capacitive shunt admittance, and considering V1=1.0pu, we have:

R=0.043pu, X=0.2287pu, V=1.041pu

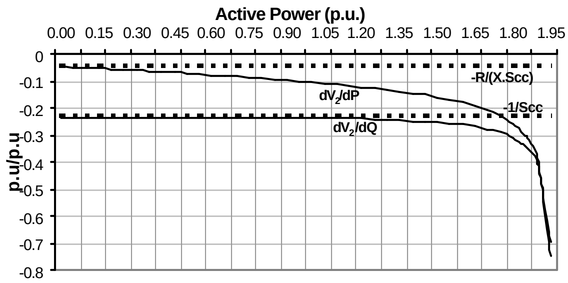

Figure 3 – Voltage sensitivity with respect to changes in P and Q for increasing system loading.

B. Analysis of the Results

Figure 3 demonstrates that equation (1) produces reasonable results for system active power loading of up to 1.2pu . This means that the short circuit power level S_{CC} provides a good indication of system stiffness, that is, the sensitivity of voltage magnitude to reactive power variation, until P=1.2pu. For transmitted active power values above 1.2pu, the voltage sensitivity become increasingly higher than the values estimated by equation (2).

It is obvious that the short circuit power level is still a good indication of system stiffness and constitutes an important reference for a quick evaluation of how much voltage is affected by small disturbances, such as faults in remote locations in the distribution system. In fact, the short circuit power -S_{CC} is an important and basic parameter that is used very frequently to assess the adequacy of the system power quality for the installation of electric arc furnaces, for the starting of large motors, etc. However, the short circuit power level is a no load system parameter and does not take into account the amount of load in the system. The simple example on Figure 2 shows how system stiffness is degraded when the system is operating at a high level of transmitted active power. In this example, such degradation occurs for relative low values of transmitted power, since the terminal voltage V2 is free to change without any control device injecting reactive power.

However, in actual radial systems, methods of voltage control are usually available at the receiving end bus, injecting reactive power to keep the voltage within the previously established range. With the assumption of maintaining V2 constant by injecting reactive power into bus 2, the sensitivity of the voltage magnitude with respect to small changes in both active and reactive power is shown on Figure 4. Under such consideration, the voltage controllability starts to become critical for P=2.5pu, with a clear indication of degradation.

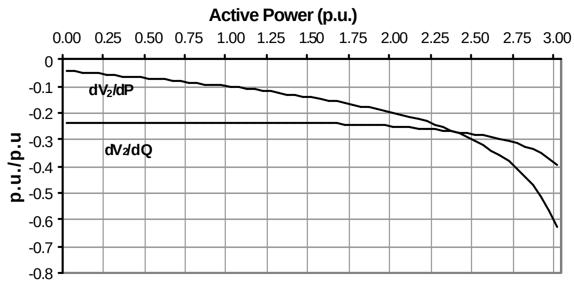

Figure 4 - Voltage sensitivity with respect to changes in P and Q for increasing system loading and with V_2=1.0pu

A convenient manner to quantify the "voltage controllability" is to measure parameter $\Delta Q / \Delta P$ (pu/pu), that is, the ratio between the required injected reactive power ΔQ into the bus to maintain the voltage constant for a variation of active power ΔP. Some experts in the operation of congested systems in Brazil recommend that

$\Delta Q / \Delta P$ should not be higher than 0.9pu/pu. Beyond this value, a new transmission line should be constructed to reinforce the system. For the simple two busses system here analyzed with a short circuit power equal to 500 MVA, $\Delta Q / \Delta P = 1.0$pu/pu for P=230 MW, and $\Delta Q / \Delta P = 1.2$pu/pu for P=270 Mw. For a transmitted power P higher than 1.2 pu, the degradation is progressively increasing as shown on Figure 5.

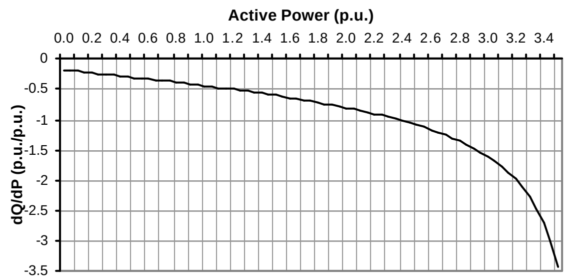

Figure 5 – Variation of $\Delta Q / \Delta P$ with system loading.

VULNERABILITY AREA ASSOCIATED WITH A SENSITIVE LOAD

Figure 6 shows the vulnerability areas associated with a sensitive load supplied from bus B1531 (69kV) of an actual regional system operating under heavy and light loading conditions, where the short circuit power is almost the same for both condition. The critical voltage level below which the sensitive load is interrupted is considered equal to 80%, regardless of the voltage sag duration. This value is corroborated by several monitoring records obtained during a couple of months and the respective interruption reports submitted by the consumer.

The noticeable difference that results from the system loading level tends to increase as the system loading becomes congested towards the point of collapse.

The expansion of the vulnerability area of this sensitive load may include the distribution level (13.8kV) where the fault incidence is much higher than the 69kV level. Including the 13.8kV level

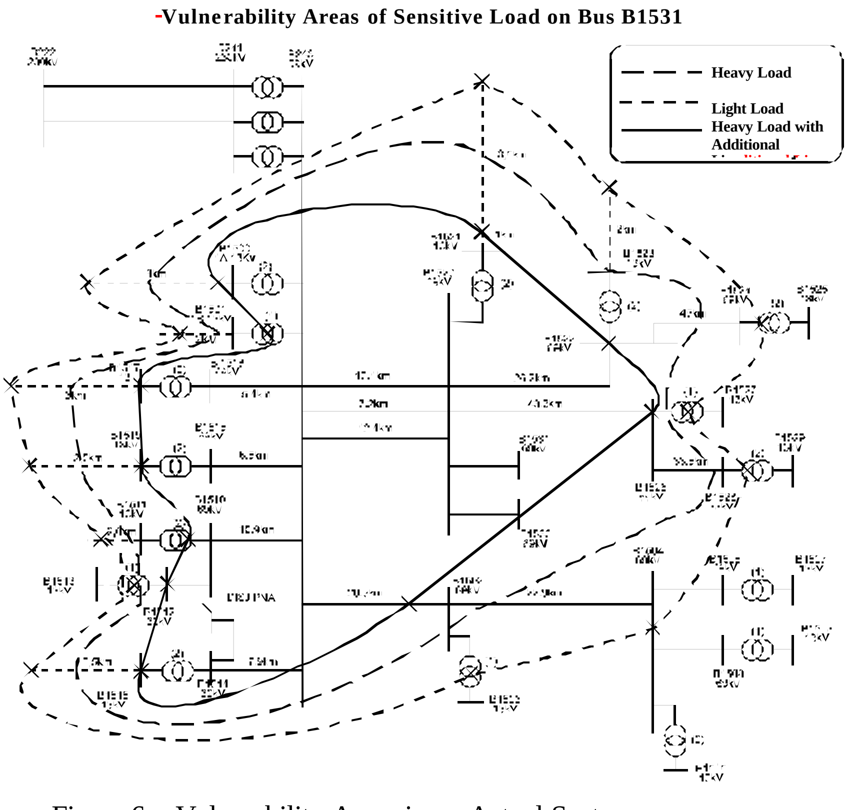

Figure 6 – Vulnerability Areas in an Actual System

distribution system, the number of load interruptions will be considerable higher, which means power quality degradation. Figure 6 also shows the vulnerability area that results from an additional transmission line, the effect of which is to increase the short circuit power and lead the system to operate under a relatively light loading condition.

The short circuit power of the simple system on Figure 2 was made intentionally 500MVA, that is, equal to the actual system under consideration. The sensitivity coefficients corresponding to P=270MW for the actual system are very similar to those obtained from the curve of Figures 3 and 4:

$$\frac{\partial V}{\partial P} = -0{,}50 \, pu/pu$$

$$\frac{\Delta Q}{\Delta P} = -1{,}3 \, pu/pu$$

A. Modeling Aspects for Obtaining the Vulnerability Area

A usual way of obtaining the vulnerability area associated with a sensitive load, installed at a certain point of the system, is by using short circuit programs. Some programs available in the market offer the capability of automatically simulating faults in each specified portion of the line, thus facilitating the analysis. As such, only the steady state of the fault is being considered, and the transient voltage decays are being neglected, but they can be of some importance if the sensitive load is located close to large energy storing sources, such as capacitor banks, motors, etc. However, this is a conservative and pragmatic approach, as a higher degree of details would be rarely justifiable by means of a program of electromagnetic transients, such as the ATP(Alternative Transient Program). Many short circuit programs, however, consider no load system condition, so that the effects of faults on voltages at different points of the system do not take into account the level of system loading. The use of short circuit programs for this purpose requires caution when dealing with weak radial and heavily loaded systems, as they may produce falsely optimistic results.

The vulnerability areas on Figure 6 where obtained using a load flow, where the loads are appropriately presented, including its characteristics with the voltage, as much as possible, in order to obtain a convergence of the iterative process. The loads of the busses near the simulated fault must be represented by a constant impedance. In the cases of imbalance faults, a short circuit program must be used with loads representation. An alternative is the use of the three-phase load flow routine that is part of the ATP.

B. System Monitoring

The installation of a monitoring system specified for the evaluation and analysis of the QEE provides invaluable inputs for the studies of QEE problem mitigation alternatives. Several simple and low-cost actions may produce important benefits – either from the consumer's side, by reducing its sensitivity, or from the power utility's side, by reducing the incidence or severity of the faults, or even by reducing the vulnerability area. Such measures may produce significant QEE improvements by reducing the number of interruptions of the sensitive loads. Under critical situations where these measures are not capable of providing the acceptable QEE level, the use of power conditioning equipment, recently made available in the market, is necessary. The selection and specification of this kind of equipment requires a detailed technical and economical analysis, the monitoring results of which play a fundamental role, as the investments involved are usually high.

POWER QUALITY DEGRADATION CAUSED BY DYNAMIC LOAD

When radial weak system supplies a relative high amount of dynamic load, as induction motors, the so called phenomenon of Delayed Recovery Voltage is likely to occur when the elimination of the faults is not achieved with short time. This are cases of overcurrent time coordinated protection relay or when second zone distance relay operate with temporization.

This problem becomes worse as much as more motor load is present on the system and as much as longer time for fault elimination is concerned. The most obvious alternative to avoid this severe power quality degradation is to use instantaneous relay operation. During the fault the numerous small motors throughout the system, driving mechanical load, start to slip, and many of them stall. Some of this motors are tripped off by protective relay but many of them, the small ones, that drive air conditioning compressors, for example, are tripped off but thermostat that take some seconds to operate. This is the case of the system under consideration that supplies power for a region with large amount of air conditioner units, mainly the small one, wall installed. The recording of rms voltage obtained from a monitoring device is shown in Figure 7. Here, the fault was eliminated by second zone relay with 1 second. After fault removal, the voltage is recovered to 80% and take a relative long time to return to normal values.

This is a dynamic phenomenon in nature and cannot be analyzed with steady state simulations tool. To reproduce this phenomenon by simulation, a detailed modeling of load dynamic is required. This is a very complex issue because the actual loads is, in true, comprised by several small motors located in different points of the system. The aggregation of these motors loads to compose one or some few equivalent motors is not a straightforward task[03].

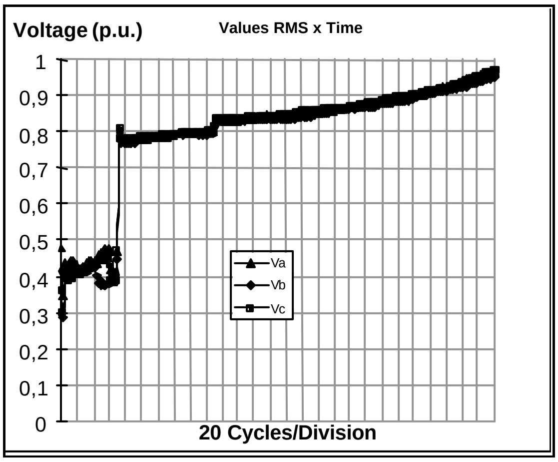

Figure 7 – Delayed Recovered Voltage obtained from monitoring.

CONCLUSIONS

The operation of high load transmission systems, especially those with predominantly radial characteristics may result in quality degradation of the electric power supplied to sensitive consumers. Such degradation results from the expansion of vulnerability areas associated with sensitive loads resulting in a higher incidence of faults.

The loading of transmission systems should be maintained below certain limits in order to preserve its inherent power quality level of the point of supply, expressed by the short circuit level. This issue, which is of utmost importance in the systems of radial characteristics, may be a requirement for construction of new transmission line.

Parameter $\Delta Q / \Delta P$ can be used as an index to express QEE, as far as the transmission loading level is concerned. Reference level 0.9pu/pu offers an interesting limit proposal to be taken into account.

The analysis of the Delayed Recovery Voltage problem demand special tools and more detailed analyses, becoming particularly important for weak, radial system with relative high presence of motor loads. One of these circumstances could be, for instance, when the employment of static shunt or series compensation is being investigated.

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