# A PROCEDURE FOR THE OPTIMAL MANAGEMENT OF LOAD SHEDDING IN LOCAL NETWORKS

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***ABSTRACT***

*For the correct continuous operation of industrial plants with co-generation, an automatic load shedding system is needed to isolate the local network in case of a fault on the utility and to shed the non-essential loads in order to contain the following frequency variation within admissible limits.*
*In this paper a general procedure is outlined for the design of the optimal load shedding scheme, which has been implemented in the program LSOS (Load Shedding Optimal Sequence). To confirm the validity of the proposed method, a simulation of its application to an industrial plant is provided.*

## INTRODUCTION

For the steady-state operation of an electrical system, the total generated power has to equal the sum of the total load consumption and the system losses: in this situation, the frequency of the system remains constant and equal to the nominal value. When a disturbance upsets this power balance, the frequency of the system begins to change.
These frequency variations, although in most cases not significant for large interconnected power systems, where they can have dangerous effects only if the faulted area separates from the rest of the power system (thus becoming an “island”), are a major concern for industrial customers with co-generation. Especially for chemical and petrochemical industrial plants connected to an unreliable external network, if the internal units do not generate enough power to cover the total load, an automatic system is needed to preserve the continuous plant operation in the case of heavy faults on the utility [1]. The task of this system is twofold: it has to isolate the industrial plant in case of a major outage on the external system, by tripping the interconnection lines with the utility, and to shed, simultaneously and automatically, the non-essential loads in order to restore the balance between internal generation and load consumption, thus avoiding the complete shut-down of the plant and obtaining an admissible frequency variation at steady state. Other actions will be taken afterwards, either manually or automatically, to restore the frequency of the system to its nominal value.
According to a traditional solution, these load shedding systems have been realised by means of electromechanical frequency relays, spread throughout the system, set to detect the decline of frequency and react automatically to drop predetermined loads. The problem of setting the load shedding sequence for the power system has usually been solved by means of trial-and-error procedures, calculating the amount of load to shed in order to face the worst possible condition and dividing these loads in three or more steps, activated by electromechanical frequency relays. Finally, in order to verify the effectiveness of the selected sequence, a dynamic simulation analysis has to be performed.
Static, microprocessor-based frequency relays are today available, which allow the implementation of much faster, real-time strategies, since the frequency thresholds of these programmable devices can be easily varied during operation: this feature allows the engineer to design a system which selects the proper shedding table in a set of tables previously prepared for different operating conditions (off-line), or even a system which calculates the load shedding sequence as soon as the emergency is detected, according to the actual loading condition of the plant (on-line or real-time system) [2].
In this paper a general procedure is presented for calculating the optimal shedding sequence, along with the corresponding tripping frequencies, on the basis of a simplified model of the system. The procedure is organised in steps, which are analysed in detail, and can be applied to a traditional electromechanical system, as well as to other kind of systems. The effectiveness of the method has been proven by means of simulation analysis: in the last part of the paper, an example of application to an industrial plant is presented.

## MODEL OF THE ELECTRICAL SYSTEM

For the simulation of the system, a simplified “single-bus” model of the system has been adopted: the isolated industrial system is considered as composed by a node, to which a single generator and a single load, representing the total internal load, are connected. The rated power of the generator equals the total generation capacity of all the internal units and its inertia constant H is calculated as the average weight of their inertia constants $H_i$ with respect to their rated powers $A_i$ [3], according to Eq.1:

$$H = \frac{H_1A_1 + H_2A_2 + ....... + H_nA_n}{A_1 + A_2 + ..... + A_n} \tag{1}$$

The variation of load consumption with voltage and the action of turbine speed regulators are neglected, thus leading to more conservative results, since their effect

would cause a smaller frequency variation in a real situation.
Let $P_G$ be the total power generated by the internal units and $P_L$ the total load consumption at time t, the overload OL (in p.u.) for the isolated system can be expressed by:

$$OL = \frac{P_L - P_G}{P_G} \tag{2}$$

The self-regulation factor d, which characterises the behaviour of the total load with respect to frequency variations (as mentioned before, we neglect any variation of load consumption with voltage) is defined by the following equation:

$$d = \frac{\dfrac{P_L - P_{L_0}}{P_{L0}}}{\dfrac{f - f_0}{f_0}} \tag{3}$$

where $P_{L0}$ is the load consumption at time t=0, f is the frequency at time t and $f_0$ is the nominal frequency. Considering the equation of the dynamics for a generator

$$J\omega\frac{d\omega}{dt} = P_m - P_e \tag{4}$$

where J is the moment of inertia of the generator, ω is its speed, $P_m$ and $P_e$ are mechanical and electrical power, respectively, and generalising to all the internal generating units, assumed to be connected in parallel, according to the approach proposed in [4], we obtain an exponential model which describes the trend of frequency vs. time by the following equation:

$$f(t) = f_0 - \frac{f_0 OL}{d(1+OL)} \cdot \left(1 - e^{-\frac{d}{2H}\dot{P}_G(1+OL)t}\right) \tag{5}$$

where OL is the initial overload at t=0 and H is the total inertia constant of the system (defined by Eq.1). The value of the settling frequency, e.g. the new steady-state value of frequency, is given by Eq.5, for t approaching infinity:

$$f_F = f_0 \cdot \left[\frac{d + (d-1)OL}{d(1+OL)}\right] \tag{6}$$

As it will be shown further, the assumptions made are reasonable and the simplified model gives satisfactory results.

## DESIGN OF THE LOAD SHEDDING SYSTEM

### Design constraints and preliminary settings

The calculation of the maximum anticipated overload is probably the most important factor in planning the load shedding scheme, since it affects greatly the following steps of the procedure: a well-planned scheme should be capable of avoiding the blackout of the power system in the worst possible condition, as well as to keep the isolated system in stable operation for any load flow condition, after tripping the tie-line with the utility. To achieve a more conservative strategy, it is advisable to assume some of the generating units to be tripped during the emergency condition and use the corresponding value of overload for the design of the load shedding scheme.
Next comes the choice of the number of steps in which the sheddable loads will be dropped: according to the above assumptions on the value of the maximum anticipated overload, the amount of load to be tripped should be large enough to compensate for the maximum overload in one shedding step. Nevertheless, the load shedding scheme is usually organised in steps, in order to avoid overshedding (e.g. the disconnection of more load than necessary) for less severe overload than the maximum expected, since this is contrary to the need for continuous operation of the plant and could even result in the loss of internal generating units due to overfrequency. On the other hand, if too many steps were involved, then a co-ordination problem among the protective relays would arise: a good choice is usually between 3 and 6 steps. The first load shedding step can be activated simultaneously upon loss of the interconnection with the utility: the corresponding tripping frequency for the relays placed on the tie line is usually set near 49.5 Hz (for 50 Hz systems). The last shedding step has to be co-ordinated with the additional relays which disconnect the generating units from the system, thus preventing the turbine blades from damage, in the case the complete blackout of the plant can not be avoided. Therefore, the tripping frequency of these relays (usually around 47.5-48 Hz, for 50 Hz systems) is usually taken as the minimum admissible frequency for the load shedding scheme ($f_{min}$); anyway, a higher value can be chosen to achieve more conservative results.

### Load to be shed per step

The first step of the procedure consists in calculating the total amount of load to be shed in order to compensate for the maximum anticipated overload and the distribution of this amount of load along the chosen number of steps. The total load to be shed is the difference between the initial overload (the maximum anticipated overload) and the value of initial overload $OL_F$ which would allow to have a settling frequency equal to the minimum admissible value without shedding any load. This value can be calculated from Eq.6, with $f_F = f_{min}$, thus leading to:

$$OL_F = \frac{d\left(1 - \frac{f}{f_0}\right)}{1 - d\left(1 - \frac{f}{f_0}\right)} \tag{7}$$

$$L_D = \frac{OL - OL_F}{1+OL} = \frac{\frac{OL}{1+OL} - d\left(1 - \frac{f}{f_0}\right)}{1 - d\left(1 - \frac{f}{f_0}\right)} \tag{8}$$

where $L_D$ is the total amount of load to be shed.

In order to share the total load out among the predetermined steps, a criterion has been adopted, based on the value of the initial slope of frequency reduction vs. time, given by the following equation:

$$\frac{df(t)}{dt} = -\frac{f_0 OL\dot{P}_G}{2H} \cdot e^{-\frac{d}{2H}\dot{P}_G(1+OL)t} \qquad (9)$$

calculated for t=0. The value of this parameter varies linearly with the overload OL, therefore it can be assumed as an indicator of the gravity of the emergency condition: if the value of the maximum anticipated overload is not very high (df/dt<2), the load to be shed increases proportionally with the number of the step, in order to minimise the load dropped in the case of less severe situations, when only the first steps of the scheme will be activated. If the maximum expected overload is very high (df/dt>2), this choice has been found to be unsatisfactory and the shedding of a big portion of load at first is necessary, therefore the total load has been divided in the opposite way: the amount of load shed decreases with the number of the steps.

**Calculation of the tripping frequencies**

The calculation of the tripping frequencies is highly dependent on the value of the frequency to trip the tie line, since it is always coincident with the shedding frequency of the first step $f_{s,1}$ (as mentioned above) and on the minimum admissible frequency. Once these two values have been set and the amount of load to be shed per step is known, the calculation of the frequency threshold for each shedding step on the basis of the simplified single-bus model defined in par.2 is rather straightforward. If we assume that the tie line is tripped at t=0, the load associated with the first shedding step will be actually cleared after the time interval ΔT:

$$\Delta T = T_{op} + T_{cb} + T_{del} \qquad (10)$$

where $T_{op}$ is the operating time of the frequency relay, which is usually constant for static relays, while for electromechanical relays it has to be read from the relay operating characteristic; $T_{cb}$ is the opening time of the circuit breaker and $T_{del}$ is an additional delay for achieving better co-ordination between steps. During this time lag the frequency of the system will go on decreasing, therefore we can calculate the value of the clearing frequency of the first step $f_{c,1}$ (the frequency at which the load is actually shed) from Eq.5, where $f_0$ is now the frequency to trip the tie line and $t = \Delta T$.

The clearing frequency of the first step (of step *i*, in general) can be assumed as shedding frequency of the next step (*i+1*), but it is advisable to consider a safety margin $f_s$ (typically 0.1-0.2 Hz) to achieve a better co-ordination between two subsequent steps, allowing for the accuracy of relays and breakers, thus obtaining:

$$f_{s,i+1} = f_{c,i} - f_s \qquad (11)$$

On the same frequency curve, a value of $T_{s,i+1}$ corresponds to this shedding frequency, which, taking into account the interval ΔT in Eq.10, permits to obtain the corresponding clearing time (see Fig.1):

$$T_{c,i+1} = T_{s,i+1} + \Delta T \qquad (12)$$

and the corresponding clearing frequency $f_{c,i+1}$. The same procedure described before can be applied to the second and subsequent steps, thus obtaining the complete list of the tripping frequencies. Finally, one has to verify that the last-step clearing frequency is not lower than the minimum admissible value; otherwise, the procedure has to be repeated choosing a higher value of the tripping frequency, reducing the safety margin or the intentional time delay.

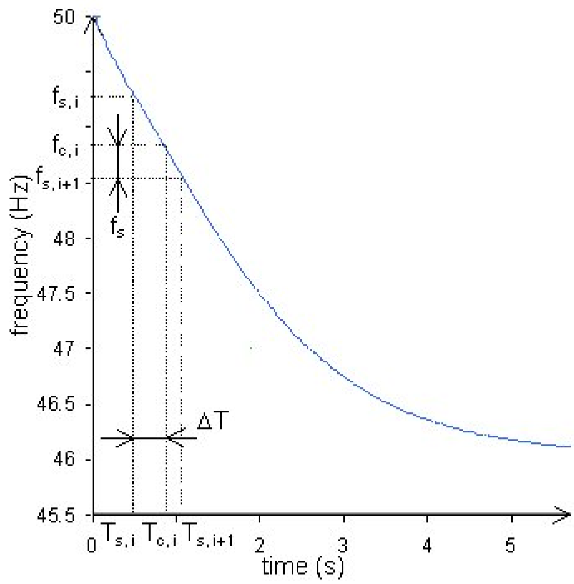


Fig.1 – Calculation of the shedding frequencies

**Optimal shedding sequence: selection of loads**

A careful analysis of the loads in the system has to be performed and general criteria have to be defined, in order to set proper priorities for shedding. In chemical and petrochemical plants, for example, many loads cannot suffer any interruption of the supply: in this paper, the priority index of these loads is set to 0, meaning that they are not included in the load shedding scheme. The priorities for the other loads have to be set according to safety and economical reasons; therefore, the loads which are shed for first (for which the priority index is set to 3) are the ones which can damage the equipment or the employees if operated in an emergency situation or loads which would probably fall out of operation automatically, when frequency or voltage fall below a specific percentage of the rated value. Loads with less economical benefit and non-critical loads in general (the lighting systems, for example) can be shed afterwards (priority 2 or 1). Critical loads which are provided with an alternative source, in order to assure continuous operation in any emergency situation, are also included in the shedding system with low priority, since they will be disconnected from the main electrical system and switched to the alternative source as soon as the disturbance is detected.

The loads to be shed can now be selected according to the list of priorities, in order to find the combination of loads of given priority, for which the total power consumption best matches the total amount of load to be shed for the corresponding step, as calculated in par 3.2. The optimal configuration is, of course, the one for which the difference between the calculated value of load to be shed and the amount of load actually dropped per step is minimum. Although other additional criteria can be defined, such as achieving a uniform distribution of loads to be shed in different areas of the system, they are not considered here.

## IMPLEMENTATION OF THE METHOD AND VALIDATION BY SIMULATION ANALYSIS

### Automatic execution of the proposed procedure

The program LSOS (Load Shedding Optimal Sequence) performs the design of load shedding systems in local networks by executing automatically the outlined procedure. It is very easy to use, thanks to its Windows-like graphical user interface.

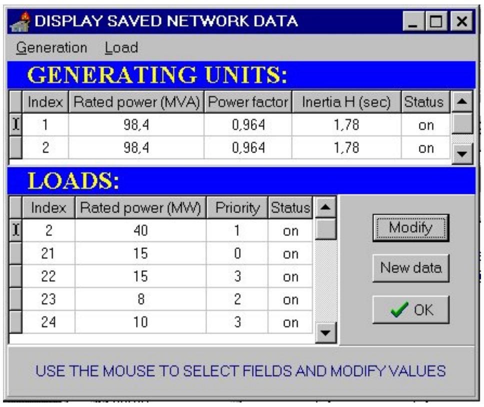


Fig.2 – Data concerning the power system

After an introductory window, the data regarding the system is displayed, in order for the operator to check and modify them, if necessary (Fig.2). The needed set of data is composed by rated power, rated power factor and inertia constant H (for generators), power consumption and shedding priority (for loads). The operator has to enter the operating status of machines and loads (on-line, off-line or stand-by) and to define the critical condition for which the load shedding scheme has to be planned. In particular, it is necessary to specify if the plant has to be assumed in the normal operating condition when the disturbance occurs, which causes the plant to disconnect from the external system, or if some generating units have to be considered off-line, thus planning the load shedding sequence for a worse condition, in which the total generation capacity is not available.

In the following window (Fig.3), the operator has to set the values of the necessary parameters: nominal frequency, disconnection frequency (the frequency at which the relay placed on the interconnection line with the external system is set to trip), minimum admissible frequency for continuous operation of turbines, number of load shedding steps, opening time of the available breakers and the factor d defined in Eq.3, which characterises the behaviour of load with respect to variations of frequency.

The program calculates the amount of overload affecting the system (in percent) and the total amount of load to be shed which is then spread over the predefined number of steps, according to the following expression:

$$\begin{cases} LS_i = \dfrac{2 \cdot L_D}{3^i} \ \ for\ i \le n-1 \\ LS_n = \dfrac{LS_{n-1}}{2} \end{cases} \quad if \ \left.\frac{df}{dt}\right|_{t=0} > 2$$
$$\begin{cases} LS_i = \dfrac{2 \cdot L_D}{3^{n+1-i}} \ \ for\ 2 \le i \le n \\ LS_1 = \dfrac{LS_2}{2} \end{cases} \quad if \ \left.\frac{df}{dt}\right|_{t=0} \le 2 \qquad (13)$$

where $L_D$ is the total load to shed (from Eq.8), $i$ is the current step and $LS_i$ is the load to be shed at step $i$.

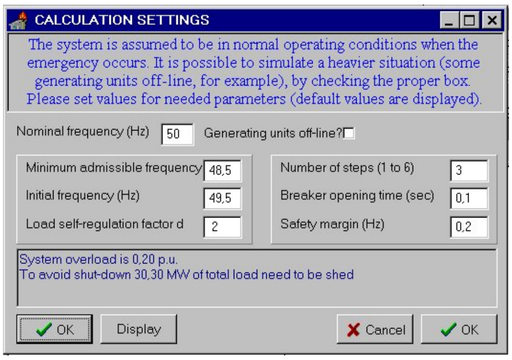


Fig.3 – Design parameters

Once the amount of load to be shed per step has been calculated, the program performs an exhaustive search of all the possible combinations of the given loads which respect the given priorities, in order to choose the one characterised by the minimum difference between the calculated value of load to be shed and the amount of load actually shed per step.

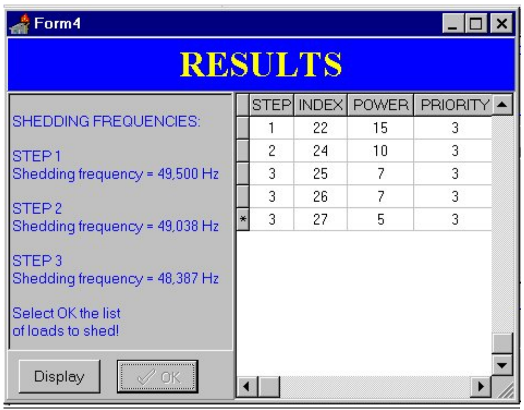


Fig.4 – Display of the results

The shedding frequencies and the list of loads to shed are displayed in a dedicated window (Fig.4), and the diagrams of frequency vs. time with or without shedding action can be plotted (Fig.5).

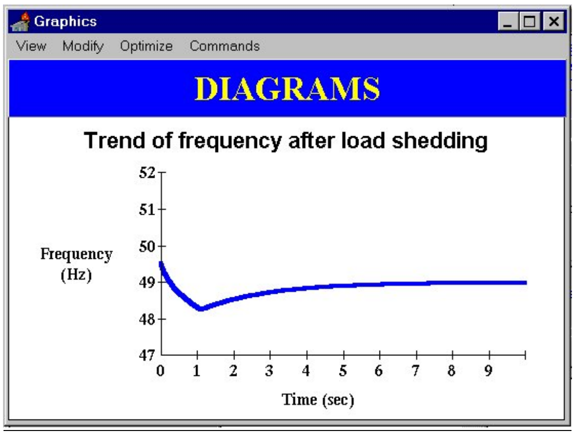


Fig.5 – Diagrams of the results

**Simulation results: validation of the model**

For the verification of the model it was assumed to consider an industrial plant with internal generated power not sufficient for supplying all internal loads, which remains isolated from the external system at t=0: the subsequent frequency variation, calculated with accuracy by means of a dynamic simulation program, is compared with the variation given by the simplified model.

The co-generation plant considered is connected to the external distribution system at a 20 kV level by means of two parallel lines and can be considered divided in two areas, each equipped by a generator, connected by a tie-line switch (normally closed during operation of the plant), in order to assure redundancy. The one-line diagram of the system is shown in Fig.6.

The CYME program CYMSTAB was chosen for performing the simulation, since it is provided with a large, complete library of models of plant components and allows the user to simulate different kinds of faults and outages. By using this program, it was possible to use accurate models for generators with their excitation systems, thus taking into account transient and sub-transient effects, while the external system was simply represented by its equivalent source (a constant voltage source with a short-circuit series reactance).

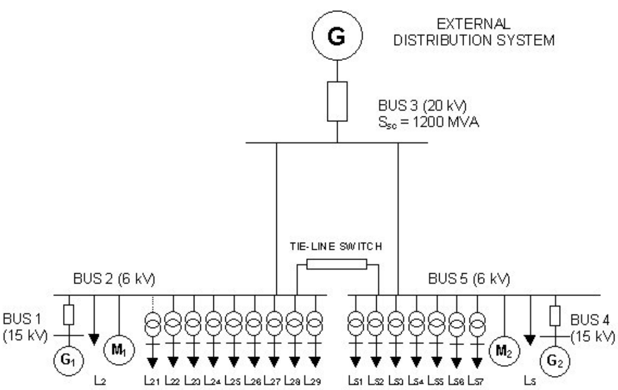


Fig.6 – One-line diagram of the system

As far as the representation of loads is concerned, three different simulations were performed, in which the total load was modelled respectively as constant power load, constant current load and constant impedance load, in order to assess the effect of the load composition and behaviour (with respect to voltage variations) on the frequency decay. The variations of reactive power with voltage have a negligible effect on the variations of frequency (as confirmed by the simulations), therefore it was assumed that the reactive power absorbed by the loads is proportional to voltage. The value of the above mentioned factor *d* was always maintained equal to 2 (a value extensively used in previous literature [4]).

The results thus obtained, shown in the diagram of Fig.7, clearly show the incidence of the type of load (the three curves are rather detached). The frequency decay predicted by the simplified model is only slightly different from the real variation in the case of constant power load, as expected since the model was derived under the assumption that the load absorbs constant power.

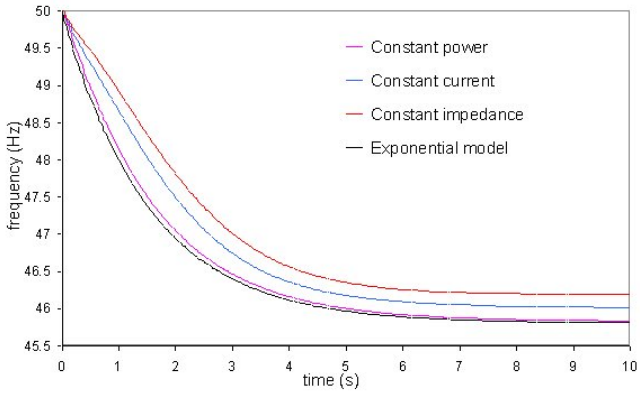


Fig.7 – Validation of the model

Although the response of the model is not so similar to the real trend of frequency in the other two cases, the predicted frequency is anyway smaller than the simulated one, and this would lead to conservative results in planning the system. In other words, a load shedding scheme planned on the basis of the proposed model, will work more effectively in a real situation, when the stabilising action of the loads and the turbine voltage regulators strengthen the reaction to the disturbance.

**Simulation results: example of application**

With reference to the above described industrial system (for which all the data is given in Table 1, together with the design parameters), a situation was assumed in which the sudden application of an additional 160 MW-load on the interconnection line causes the frequency to decay, thus simulating a disturbance on the external system. By using the program CYMSTAB, the presence of underfrequency relays at appropriate nodes was simulated: the relays on the interconnection lines were set to trip at 49.5 Hz, while frequency thresholds and delay times for the other ones were set according to the sequence given by the program LSOS (shown in Table 2), with a minimum admissible frequency equal to 48.5 Hz and fs=0.1 Hz.

As a result, the curves shown in Fig.8 were obtained, for the three different types of loads (constant power, curve 1; constant current, curve 2; constant impedance, curve 3): it can be seen from the trends of frequency that the adoption of the shedding sequence given by the program allows to maintain the stable operation of the plant and when, at the end of the transient, the new steady-state condition is reached, the difference between actual and nominal frequency is maintained within the admissible limits.

**Table 1 –Data of the system and design parameters**

| | |
|---|---|
| Total load consumption | 228 MW |
| Motors $M_1$, $M_2$ | 6 kV, 2 MW, H=10 s |
| Motors $M_{23}$, $M_{53}$ | 380 V, 250 kW, H=10 s |
| Total generation capacity | 190 MW |
| Generators $G_1$,$G_2$ | 15 kV, 107 MVA, H=1.78 s |
| Nominal frequency $f_0$ | 50 Hz |
| Minimum adm. frequency $f_{min}$ | 48.5 Hz |
| Frequency margin $f_s$ | 0.1 Hz |
| Number of steps | 3 |
| Opening time of the breakers | 0.1 s |
| Delay | 0 s (first step), 0.1 s (further) |

**Table 2 – Shedding sequence**

| STEP | FREQUENCY | LOAD | POWER (MW) |
|---|---|---|---|
| 1 | 49.5 | 27,57 | 15 |
| 2 | 49.138 | 26 | 10 |
| 3 | 48.575 | 22 | 19 |

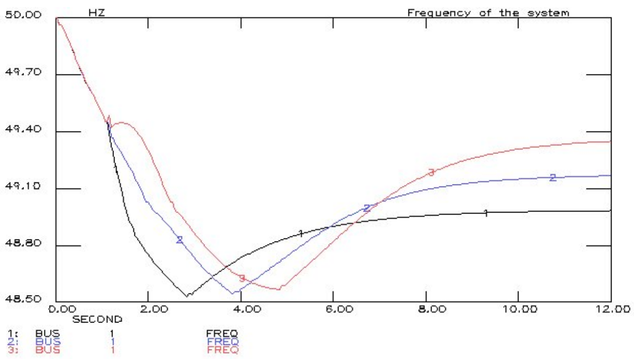


Fig.8 – Trend of frequency vs. time (normal operation)

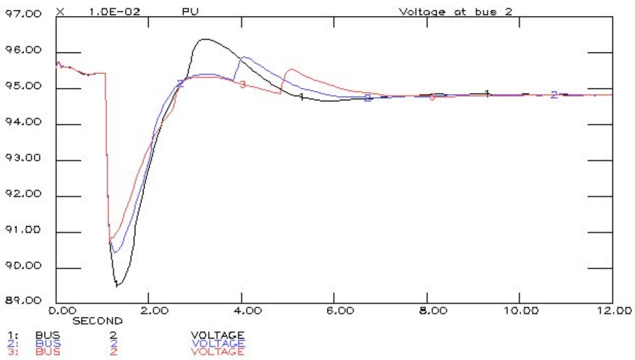


Fig.9 – Voltage at bus 2 (normal operation)

The diagram of Fig.9 shows the trend of voltage at bus 2 in the three different simulations, from which it can be seen that the values assumed by the voltage during the whole transient are acceptable.

The same sequence has been proven to be effective also in other situations, in which the total load connected is less than the maximum, due to internal outages or to variations in the load cycle: assuming, for example, that load no.21 (rating 15 MW) is not supplied when the plant remains isolated, the diagrams of Fig.10 show that a stable condition is reached, as well as in the preceding case. Moreover, the maximum transient variation of frequency is smaller, since only two steps of the sequence are activated.

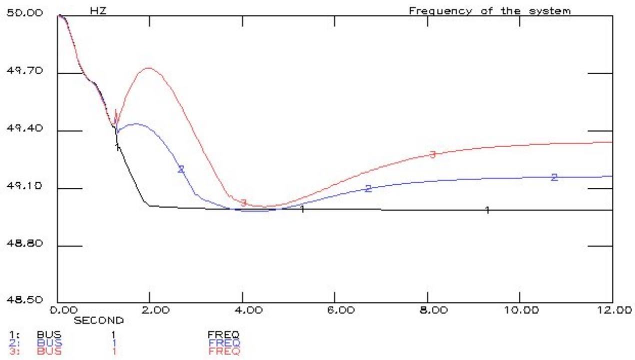


Fig.10 – Trend of frequency vs. time (load 21 disconnected)

## CONCLUSIONS

The exponential model of the industrial power system, although derived under some simplified assumptions, gives satisfactory results: the curve of frequency vs. time is very near to the real one, at least in the case of constant power load. In any case, the model can be used to plan the load shedding sequence for an industrial power system, because in the realistic situation of mixed load it predicts a variation of frequency which is higher than the real one, thus leading to conservative results.

The program LSOS, developed on the basis of this system model, given the data regarding the plant and the values of the necessary design parameters, gives a load shedding sequence which permits to maintain the stable operation and contain the steady-state frequency variation within admissible limits, as shown by means of the examples of application to a realistic industrial power system.

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