Experimental Determination and Numerical Simulation of the Dynamic Insulation of a Large Consumer Unit

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Abstract: - The paper gives full details of the results obtained by means of the experimental tests by islanding the vital consumers within the power system of Hunedoara Iron Works from the own electric source. These results are compared to the ones obtained by mathematical simulation. The drow up computation programs being validated by the experimental tests, they become useful means for the analysis and optimization of local power system operating regimes.

Key-Words: - power system, mathematical simulation, large consumer unit, long term dynamics, synchronous generator, steam turbine, boiler, electric network

1 Introduction
The continuity of supplying large industrial consumers with electric power implies complex multiple problems, especially in the circumstances of producing some disturbances in the power system, when their insulation by means of their own power sources is necessary.

In these situations, the microsystem resulted from the insulation reaches a stationary regime through a transient process which raises stability problem at the first oscillations of the electromagnetic and thermo-mechanic values of the supplying sources and, for a larger time, of tens of seconds, due to the lower performances of their own controlling and protecting systems. Thus, an appropriate mathematical simulation is very important for optimizing operating conditions, control adjustment and finding adequate solving solutions.

The paper presents the experimental results obtained from the insulation based on a self power source of a microzone within the electric power system of Hunedoara Iron Works. The results are then compared with those of a mathematical simulation realized by means of an algorithm and a program conceived by the author. It is the synthesis of a research work realized in two years.

2 Description of the Studied Microzone
The power system of Hunedoara Iron Work is a complex one, operating on five voltage levels (220 kV; 110 kV; 35 kV; 6 kV and 0.4 kV), with a high density of 6 kV network and with a large number of different types of consumers. This power system preserve the general structure of the power systems of iron works units being based on the principle of increased safety of operation, realized by double supplying of the interconnection and distribution stations and the existence of its self electric power source (CET-2) capable to cover the power necessary for the vital consumers in case of a shut-down with total detachment from the National Power System.

The vital consumers concentrated around the producing and consuming station (SPC) are supplied with 6 kV voltage from a double system of buses connected to the self power plant and to the National Power System, like in Fig. 1. In normal operating conditions most of the vital consumers are supplied from bus I of SPC station, interconnected with bus II by the closed bus-bar coupling, the power injection being realized from the National Power System, connected to bus II and the self power plant (CET-2) connected to bus I. The microzone studied in this research work is made by the set ensemble of buses I and II of SPC station together with the vital consumers. In case a shut-down in the National Power System or on the interconnected line with SPC station, by switching on the key-socket of the bus-bar coupling between bus I and bus II of SPC station, the insulation of the microzone is realized and its vital consumers will operate being supplied with the power of self power plant, CET-2.

By switching on the key-socket of the coupling bus-bar there has been determined a transient process of CET-2 power unit which can lead to the tripping of the synchronous generator of the self power plant, CET-2, either at overload or at overspeed. This reason determines the necessity of knowing the operating conditions of CET-2 in long term dynamics (tens of seconds or even minutes) generated by different values of the power passing through the cross bus-bar in ante-emergency steady state.

The analysis of CET-2 transient behaviour can be realized through mathematical simulation, but the correctness of the mathematical model and validity of the results can be made by comparing them with the experimental results, obtained in a real insulation process.
3 The Insulation Experiment

The following problems have been solved in order to realize the experiment: determining the steady state before shut-down; determining the power passing through the transfer coupling; choosing the measuring equipment and its insertion in the experiment with the registration of time-based variations of the main electromagnetic and thermo-mechanic values and restarting the generation of power plant CET-2 in parallel with the National Power System, in case of success of the insulation process.

The pre-shut-down steady state has been realized so that the microzone studied benefit from an excess of electric power generated by 0.23 p.u. power passing-by to the National Power System through the interconnecting station, SPC. The voltages and electric power in the microzone buses in pre-shut-down, steady state obtained by direct reading two minutes before the moment of insulation are given in Table 1 and expressed in p.u.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage [p.u.]</th>
<th>Active power [p.u.]</th>
<th>Reactive power [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generated</td>
<td>Consumed</td>
<td>Generated</td>
</tr>
<tr>
<td>1</td>
<td>0.982</td>
<td>-</td>
<td>0.23</td>
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<tr>
<td>2</td>
<td>0.984</td>
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<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.971</td>
<td>-</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.976</td>
<td>-</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>0.969</td>
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<td>0.13</td>
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<tr>
<td>7</td>
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<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>8</td>
<td>0.972</td>
<td>-</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 1. Voltages and electric powers in steady state buses

For gathering and registering the variations in time of the electromagnetic values of the synchronous generator in CET-2, during the transient process of insulation there have used portable registering instruments. For the registration of the thermo-mechanical values and of the frequency in the microzone we have used registering panel instruments, fixed on the panel of the switch room of the self power plant, CET-2. By the command of switching on the key-socket of the coupling bus-bar (see Fig. 1) SPC microzone has been separated bar I of the National Power System, the microzone becoming a generating isle, the self power plant, CET-2, being loaded with an excess of electric power of 0.23 p.u.

The transient phenomena have been followed for 98 seconds (1 minute and 38 seconds) when it has been considered that the post-shut-down steady state of the insulation is reached and we have passed to switching on its self generation unit in parallel with the National Power System.

The registration of the dynamics of electric, mechanic and caloric values: voltage at the clamps, $U_b$, the electric power discharged on the power plant bar, $P$, frequency, $f$, steam capacity, $m_{HP}$ and steam pressure, $p_s$, at the entrance in the steam turbine presented in the diagrams of Fig. 2 and Fig. 3, show a good behaviour the unit boiler-steam turbine-synchronous generator on both primary (steam capacity, steam pressure) and secondary (voltage, electric power and frequency) side. The analysis of the dynamics of the insulation process has showed that the transient phenomena have a long time, of about 40-50 seconds, being relevant through three strong oscillations of the electro-mechanic values (voltage, electric power, frequency), followed by a period of quieting which in about 80 seconds leads to reaching the steady state post shut-down, characterized by very good values of the electromagnetic, mechanic and caloric parameters of the self power plant CET-2.

Fig. 1. The simplified electric diagram of the studied microzone

Fig. 2. The experimental determination of the variation in time of the thermic values in the insulation process

Fig. 3. The experimental determination of the variation in time of the electric and mechanic values in the insulation process
4 Mathematical Simulation of the Dynamic Process of Insulation

The experimental results obtained in the process of the microzone insulation have showed that the evolution of the thermo-mechanic phenomena of the self power station can be framed in the problem mid-term or even long term dynamics of the power systems. That is why, in conceiving the mathematical models, the algorithm and the program we have taken into account some of the hypotheses of such dynamics, concerning the frequency calculus in the microzone, the adaptation of the programme steps and incremental values of the calculus time, the extensions of the numerical simulations to the primary units, the modifications of the respective parameters of the electrical network according to the frequency and total durations of the analyses time. The mathematical models of the system elements of the primary units of consumers (boiler, turbine, primary control elements, synchronous generator, excitation and voltage control system, electrical network and consumers) used for the mathematical simulation will be further described.

a) The model of the steam boiler and its automations

As a controlled object, the boiler has been represented by two concatenated elements, like in Fig. 4, which represents the combustion chamber and the steam generator.

![Diagram of steam boiler](image)

Fig. 4. The steam boiler as controlled object

The controlled value, steam pressure, \( p \), is modified through heat quantity variation, \( \Delta Q \), produced by the combustion, chamber because of the fuel and our flow modification, respectively \( \Delta B \) and \( \Delta A \), at the entry into the combustion chamber, as well as because of the steam flow variation \( \Delta D \) required by the dawn-stream consumers.

The steam generation can be represented through a first rank delay transfer function, if operation \( s = \frac{d}{dt} \) is introduced, that is

\[
H_C = \frac{1}{1 + T_p \cdot s}
\]

where \( T_p = T_a \frac{p_m}{D_{max}} = (125 \div 300) \text{sec} \), is the inertia time constant defined by means of the accumulation constant, \( T_a \left[ \frac{kg}{at} \right] \) and \( p_m \) is the nominal steam pressure and \( D_{max} \) is the maximum steam load.

For the mathematical simulation of the chamber there has to be taken into account the fact that its influence on the boiler dynamics depends on both the fuel burning method and the structure of the combustion chamber. The heat emitted in the combustion chamber is determined by the control system of the burning process. This control system contains the fuel feeding system and the fuel control system, which react to the steam flow and pressure emitting a modification impulse of the fuel flow, which, after a period of time, due to the delay in the fuel feed system, starts modifying the thermal load, \( D_p \). With the steam drum boilers, the process of thermal load modification is described by the differential equation:

\[
T_F \frac{dD_q}{dt} + D_q = \mu_B \cdot e^{-\frac{t}{T_C}}
\]

where \( T_C = (6 \div 60) \text{sec} \) – time constant fuel transportation; \( T_F = (20 \div 25) \text{sec} \) – combustion chamber time constant; \( \mu_B \) = fuel feed control unit position.

With boilers, where their dynamics is determined by the rapid water-steam way, the steam generator influence is much more reduced than the delay introduced by the water feed pumps that can be represented by a transfer function as it follows:

\[
H_p = \frac{1}{1 + M \cdot s}
\]

where: \( M = (20 \div 25) \) seconds is the water feed pump time constant.

The automatic control system of the steam boiler aims at load control fuel burning control water level maintenance with steam drum boiler, maintenance of steam temperature and the constant maintenance of the negative pressure in the combustion chamber. The mathematical simulation of these functions is practically translated into the simulations of the following control units that of steam pressure, that of air and fuel, of water feed and of temperature. As the temperature modification and control is very slow, their mathematical simulation can be neglected.

The fuel air control method, specific to steam drum boilers has been represented by a delay transfer function as \( \frac{1}{1 + T_p \cdot s} \) and a delay \( e^{-st} \), given by fuel feed and
the control method of water/steam dynamics, specific to boilers which has been represented through a P-I control unit expressed by \( \left( \frac{K_w}{s} + \frac{K_w}{s} \right) \) with the corresponding limits. The pressure control equipments are represented through a pressure control P-I unit expressed as \( \left( K_p + \frac{K_r}{s} \right) \) followed by a differential control element expressed as \( \frac{1 + T_k \cdot s}{1 + T_k \cdot s} \).

**b) The mathematical simulations of the steam turbine**

The energetic status modifications of the steam turbine can be generated by the following disturbing values variations of the electric load of the generator driven by the steam turbine, steam flow variations in the boiler, steam pressure variation coursed by the modification of fuel caloric power; reversed pressure variation due to the pressure modification in the condenser and steam flow variation at the sockets.

The effects of these disturbing values are compensated by the actions of the turbine control system which aims at its speed modification according to the necessity of power. That is why, within the mathematical simulation, the mathematical simulation of the automatic speed control has to be added to the mathematical simulation of the turbine.

A simplified representation of the steam turbine with three pressure units is given in Fig. 5.

![Fig. 5. The general diagram for the mathematical model of the steam turbine with three pressure units and overheater](image)

The steam turbine is modelled through two first rank delay transfer functions, representing the delays given by the intermediate overheater and the steam transfer between the unit of medium pressure and the unit of low pressure, as well as through three corresponding transfer functions \((F_{HP}, F_{IP}, F_{LP})\) corresponding to the weight of low, medium and high pressure units. The entry value of the mathematical model of the steam turbine is the steam flow \((m_{cv})\) from the output of the set of pipes, slide valves and speed control unit and the output value is mechanical power \(P_m\), at the turbine axle.

The steam turbine speed governor is a static control, with its station between \((1\div7)\%\), in order to make possible the unique processing and modification of the disturbing values according to necessities. For the mathematical simulation of the steam turbine speed control unit, there has been chosen a general model, described by the diagram in Fig. 6.

![Fig. 6. The diagram of Speed Governor model](image)

Based on the mathematical models of the main thermo-mechanic elements there has been conceived an operating diagram for the set of primary installations of the thermoelectric station which describes mathematically the operation of the corresponding physical system. The diagram is presented in Fig. 7.

Based on the diagram of the primary thermo-mechanic installation in Fig. 7 there has been written the set of differential and algebraic equations through which there has been described mathematically the operating conditions of these installations in dynamic regime.

**c) The simulation of the synchronous generator on the canals of electromagnetic and electro-mechanic influence**

In the dynamic processes, the synchronous generator \((SG)\) will suffer remarkable influences both on the electromagnetic and the electro-mechanic canal, its behaviour being determined for the Power System \((PS)\) in some stages \((up to the quenching of the electromagnetic phenomena, followed by a finite disturbances)\) and it will be determined by the Power System, through the dynamics of the primary installations in other stages of the dynamic processes. Their mutual influence \((SG\div PS)\) is represented in Fig. 8.
In order to establish the mathematical models of the synchronous generator, taking into account the specificity of the problem approached, there is the necessity a true to reality modelling of the phenomena and parameters which influence sensibly SG behaviour in the dynamic regime, namely the phenomena in the iron core of the synchronous machine. We must also say that using system equivalents or a hierarchy of SG mathematical models according to their distance from the place disturbance is inopportune because in Long Term Dynamics, only the position of the first disturbance is known. The first disturbance may cause a chain of other random disturbances whose appearance cannot be known beforehand. Consequently, the mathematical SG models must be unique and complex for all of the SG of Power System. The SG mathematical models based on Park’s equations of the theory of two axes, but to which more simplifying hypotheses have been applied. Thus, if the dynamic processes are longer than 3 – 4 seconds, the synchronous generator can be simply represented by an electromotive voltage source behind the transient reaction, Fig. 9. This voltage is of a constant value, but it changes position versus a reference axis chosen randomly arbitrarily.

Fig. 7. The operating diagram of the set of thermo-mechanic installations of a power plant

Fig. 8. The diagram of connecting the synchronous generation to the Power System

Fig. 9. The simple representation of the synchronous generator
The voltage behind the transient reactance is determined from the relation:

$$E = U_b + RI + jX_q I$$  \hspace{1cm} (4)

and taking into account the flows along the two axes in quadrature, “d” and “q” we can calculate a fictitious voltage following axis “q” behind the synchronous reactance, $X_q$.

$$E_q = U_b + RI + jX_q I$$  \hspace{1cm} (5)

The sinusoidal flow produced by the excitation current act along axis “d”. The voltage induced by it remains $\frac{\pi}{2}$ electric degrees behind and it is to be found in axis “q”. This electromotive voltage can be determined adding to the voltage at the terminals, the drop in voltage on the resistance of the fixed coil winding and the drop in voltage representing the demagnetizing effects after axes “d” and “q” where $E_t$ is e.m.v. (electromotive voltage) corresponding to the excitation current. In Fig. 10 we have represented the vector diagram corresponding to e.m.v. $E_t$.

![Fig. 10. The vector diagram corresponding to e.m.v. $E_t$](image)

Starting from the vector diagram we can calculate e.m.v. $E_q$, corresponding to the winding of the excitation flow which results from the combination of the effect $t$ of the excitation currents and fixed coil currents. We have also added to it the saturation effect of the wound core, introduced through a saturation function, $f_{sat} = 0.1 \cdot E_q$, that is:

$$\frac{dE_q}{dt} = \frac{1}{T_{d0}} (E_{fd} - E_t) + f_{SAT}$$  \hspace{1cm} (7)

where $E_{fd}$ – e.m.v. corresponding to the excitation field controlled by A.V.R., $E_t$ – e.m.v. corresponding to the excitation current and $T_{d0}$ – the transient time constant.

With these hypotheses, the model of the synchronous generator on the electromagnetic canal, in dynamic regime, can be built following an algorithm which takes into account the inclusion of the synchronous generator in the model of the electric network for determining the power flow in dynamic regime. The algorithm of the representation of the synchronous generator on the electromagnetic canal, in dynamic regime is the following:

-- at each computing step and for each bus:
A1: if the bus is not of a generator type, we pass to A14;
A2: knowing the active and reactive power and the voltage at the terminals, from the previous step, we calculate the active and reactive element of the load current.

$$I_a = \frac{P}{U_b}; \hspace{1cm} I_r = \frac{Q}{U_b}$$  \hspace{1cm} (8)

A3: the generator load angle is determined

$$\varphi = \text{arctg} \left( \frac{Q}{P} \right)$$  \hspace{1cm} (9)

A4: the generator internal angle is calculated:

$$\Phi = \text{arctg} \left( \frac{I_a \cdot \omega L_q - I_r R}{U_b + I_r \omega L_q + I_a R} \right)$$  \hspace{1cm} (10)

A5: the total angle is calculated:

$$\psi = \Phi + \varphi$$  \hspace{1cm} (11)

A6: the polar e.m.v. is determined, following axis “q”, $E_q$, in module based on a program of current circulation on synchronous impedance:

$$E_q = \left[ (U_b + I_r \omega L_q + I_a R)^2 + (I_r \omega L_q - I_a R)^2 \right]^{1/2}$$  \hspace{1cm} (12)

A7: calculating the value of total load current and of the components following current axes “d” and “q”:

$$I = \left( I_a^2 + I_r^2 \right)^{1/2}; \hspace{1cm} I_a = -I \sin \varphi; \hspace{1cm} I_q = I \cos \varphi$$  \hspace{1cm} (13)

A8: determining value e.m.v., $E_t$ corresponding to the total current:

$$E_t = \left[ (U_b + RI)^2 + (\omega L_d I_a + \omega L_q I_q)^2 \right]^{1/2}$$  \hspace{1cm} (14)

A9: the intervention SRAT is considered and it will determine value e.m.v., $E_{fd}$ corresponding to the excitation field;

A10: determining the value of the component following axis “q” of a transient e.m.v., $E_q'$, taking into account the saturation:

$$\frac{dE_q'}{dt} = \frac{1}{T_{d0}} (E_{fd} - E_t) + f_{SAT}$$  \hspace{1cm} (15)

A11: if S.G. considered has no damping winding, its component following axis “d”, of $E'$, becomes $E_d' = 0$ and it jumps to A13;

A12: if the SG considered has damping winding, we calculate:

$$E_d' = \frac{E_q - E_q'}{\tan \psi}$$  \hspace{1cm} (16)

A13: the complex expression, corresponding to plan $d$-$q$ results in:

$$E = E_d' + jE_q'$$  \hspace{1cm} (17)
A14: the rotor movement equation is solved and, in this case, it will be influenced only the presence of the damping winding (by factor $D_1$), namely:

$$\frac{d\omega}{dt} = \frac{1}{T_1}[P_m - P - D_1(\omega - \omega_0)]$$  \hspace{0.5cm} (18)

$$\frac{d\delta}{dt} = \omega - \omega_0$$  \hspace{0.5cm} (19)

where $P_m$ – mechanical power at the turbine axle, which is obtained solving the equation system corresponding to thermo-mechanical installations.

$A_{15}$: Determining the transient e.m.v. components, $E'$, following general axes $X$ and $Y$ of the complex plane of the electric network, namely:

$$E'_X = E'_d \sin \delta + E'_q \cos \delta$$

$$E'_Y = E'_q \sin \delta - E'_d \cos \delta$$  \hspace{0.5cm} (20)

$A_{16}$: Calculating the transient value and e.m.v. phase are $E$, in the complex plane of the electric network:

$$E = \left( E'^2_X + E'^2_Y \right)^{1/2}$$ ;  \hspace{0.5cm} \delta' = \arctg \left( \frac{E'_Y}{E'_X} \right)$$  \hspace{0.5cm} (21)

A17: Passing the next bus.

To this computing algorithm, there are added the equations which describe the operating system SE-AVR, whose operating diagram is given in Fig. 11 and whose transfer function is:

$$F_s(s) = \frac{K_i K_E}{(1 + T_i s)(1 + T_r s)}$$  \hspace{0.5cm} (22)

by the bus admittance matrix $[\mathbf{Y}]$. The link between the bus status values (bus voltages, $U_n$, current, $I_n$ and bus injected powers, $S_n$) is described by the matrix equations:

$$[I_n] = [\mathbf{Y}] \cdot [U_n] ; \hspace{0.5cm} [S_n] = [U_n] \cdot [L_n]$$  \hspace{0.5cm} (23)

The determination of power system status at certain moments implies to know all, the status values in all the buses at the moment, fact that implies solving the equation system (23), namely determining the power flow.

$e)$ Considering the electric consumers

The consumers participation in the modification of power system status electric values is described by the consumer characteristics which represent the dependence of the status values specific to consumers (active, and reactive power, sliding etc.) on the status electric values provided by the system (voltage, frequency) at their terminal. Getting to know exactly the characteristics of the complex consumers would allow their proper mathematical simulation, influencing sensibly the possibilities of precise determination of the respective stability system limits and its operating conditions.

But the characteristics of the complex consumers depend on a lot of factors, namely: season, day time, individual receiver combinations in the complex consumer architecture etc. All these factors have a random quality, making impossible an accurate knowledge of their characteristics. In this paper taking into account these observations, the complex consumers in the consuming buses of the power system have been simulated mathematically in a simplified form know as $P = \text{constant}$ and $Q = \text{constant}$.

$f)$ The numerical simulation of the microzone dynamic insulation

In order to simulate the insulation process dynamics SPC microzone within the power system of Hunedoara Iron Work, the data base taken into account is the real situation of the microzone at the moment of the insulation experiment. The entry data for the programme have been the real parameters of the electric network, the voltage and powers measured in the microzone buses a few seconds before switching on the bus bar coupling between bus I and II, the thermo-mechanic values (pressure, steam flow) registered at the moment of disturbance and the catalogue data of all the system elements.

The numerical simulation has comprised all the stages of the insulating process, from determining the pre-disturbance stationary regime to reaching the post-shut down stable regime of the emergency insulation. The moment of switching-on of the bus bar coupling has been simulated by a scenario of breaking side 1-3 within the microzone circuit arrangement, represented in Fig. 1.

The dynamic phenomena of the insulation process have been simulated in an interval of 120 seconds up to reaching a sure stable post-emergency regime. The results of the
numerical simulation are represented graphically, through drawing the corresponding oscillation curves of the electric, mechanic and caloric values. These oscillation curves are presented in Fig. 12 and 13. For the graphical representation of the results there have been used adequate scales for each value, so that there should be a symmetry of the extreme values that allow a clear qualitative appreciation of the dynamic insulation process and offer the possibility of an immediate comparison with the registrations obtained during the experiment.

The analysis of the results of numerical simulation compared with the ones obtained experimentally shows a good concordance between simulated and real dynamics. The results of the numerical simulation are very close to these obtained experimentally. For example, in the stationary post-emergency regime, the voltage values at the terminals differ by 3% from the real ones and the powers at the terminals result in a difference of about 4.3% between the calculated values and the measured ones.

5 Conclusion
The results of the numerical simulation being in concordance with the experimental ones, there can be stated that the mathematical models and the computing algorithm represent realistically the physical phenomena in both stationary pre-emergency regime and the dynamic insulation process.

Validating experimentally the mathematical models and the numerical simulation programme of the insulation dynamics, specialists may benefit from a very useful instrument of analyzing the operating conditions of power systems and the possibility of a contingency plan which allows optimum operating conditions and appreciation of the necessary actions of passing to insulation in critical situations. It also allows getting useful results for further studies of power system expansion.

References: