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Monte-Carlo simulation of electricity transmission system operation ⋆

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Abstract: One of basic system services that an electricity transmission system operator guarantees is power balance maintenance. The aim of this service is to keep power export/import to/from surrounding interconnected electricity transmission systems at a proposed value. The power quantity is a random variable. Therefore, a control strategy of the quantity consists in keeping amplitudes of a power balance deviation in specified boundaries. The operator uses so called ancillary services for this purpose. In order to verify that power reserves of particular ancillary services are large enough for guaranteeing reliable operation of the electricity transmission system a Monte-Carlo simulator has been developed and implemented. The simulator models dynamical behavior of the system under the power reserves constraints.

Keywords: Modelling, operation and control of power systems

1. INTRODUCTION

Modelling of dynamical processes in an electricity transmission system plays a very important role in planning of system operation for specific time-horizons. The problem of the modelling has even become more crucial since a market with electricity and ancillary services has been established because this namely brings more uncertainty into operating the system with respect to its reliability.

The system operation planning is a fundamental task for every local electricity transmission system operator (TSO). Each European TSO is charged with duties specified by domestic laws as well as international rules for interconnected electricity transmission system operation administrated by UCTE (Union for Coordination of Transmission of Electricity) UCTE [2004].

In order to meet the duties, a TSO purchases and uses a set of power reserves called ancillary services. Those reserves are allocated on certain power units and are employed by a dispatcher in such a way that proper control strategies are proceeded in order that the duties are satisfied.

One of main goals of the TSO is to perform overall volume and structure optimization of ancillary services when the system operation planning is found under construction. The optimization has two essential directions – technical and economical, respectively. This paper entirely deals with the technical point of view. The optimization is performed through several basic steps.

At first, a power balance deviation of the system in an open loop mode (without any control actions) is statistically and probabilistically modelled Anderson [1971], Papoulis and Pillai [2002]. This stage includes models of undisturbed system operation (without any forced power unit outages) and of forced power unit outages (the Gaussian distribution and Markov process are employed in the modelling). Those models are parameterized by values obtained from statistical processing of real monitored data and signals.

Subsequently, overall volume of ancillary services needed for a required level of system operation reliability is determined from the technical viewpoint. The volume is computed from a Gaussian sum that integrates the models of undisturbed system operation and forced power unit outages. The volume is then separated into power reserves of particular ancillary services, which is given by characters of deviations that should be eliminated by corresponding types of the services. The models described above are presented in Janecek et al. [2006], Janecek et al. [2006].

Further, economical optimization of the technical power reserves of the services is performed taking into account their availability on the market with ancillary services as well as their prices on the market Havel et al. [2007].

The final stage of the whole optimization procedure consists in verifying that the economically optimized power reserves of the services are large enough for required reliable operation of the system in a closed loop mode (with control actions). For this reason, a Monte-Carlo simulator that models and simulates dynamical behavior of the system in the closed loop mode has been developed.

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It has two basis parts. The first one involves dynamical models of system operation in the open loop mode (the models of undisturbed system operation and of forced power unit outages) and the second one consists of dynamical models of ancillary services (models of their activations/deactivations, setpoints and trends). When a Monte-Carlo simulation of the system operation is finished, the simulator performs evaluation of the simulation from the reliability point of view and provides appropriate results.

It should also be claimed that all the models mentioned above have been software-implemented with MATLAB, Simulink as a complete program package that is used by the Czech Electricity Transmission System Operator – member of UCTE for the system operation planning.

2. MAIN IDEA

At the beginning, relevant monitored data and measured signals have been recognized from the system operation reliability point of view. Since the reliability of the system operation is particularly linked with power balance control here, those data and signals have included a power balance deviation in the closed loop mode $dP_{ct}(t)$, power control injections $R(t)$ supplied to the system by activations/deactivations of ancillary services, starts and ends of forced power unit outages and time durations related to the outages (times between failures and of repairs). The deviation $dP_{ct}(t)$ is then decomposed.

2.1 Decomposition of $dP_{ct}(t)$

It holds that:

$$dP_{ot}(t) = dP_{ct}(t) + R(t), \tag{1}$$

$dP_{ot}(t)$ is a power balance deviation in the open loop mode. The deviation represents behavior of the system without any control actions and it is easily obtained from (1). The deviation can be expressed as follows:

$$dP_{ot}(t) = dP_o(t) + T(t), \tag{2}$$

$dP_o(t)$ is a power balance deviation in the open loop mode of undisturbed system operation (without any forced power unit outages) and $T(t)$ constitutes the outages. The deviation is obtained by excluding sectors where the outages occur from $dP_{ot}(t)$. Those sectors are identified in virtue of the information about the starts and ends of the outages. The components $dP_o(t)$ and $T(t)$ are modelled.

2.2 Probabilistic model of $dP_o(t)$

Whereas $dP_o(t)$ is a random variable, it is modelled by a proper distribution from a probabilistic viewpoint. It has been proved by fit tests that the most proper distribution for modelling $dP_o(t)$ is the Gaussian distribution:

$$f_G(dP_o) = \frac{1}{\sqrt{2\pi}\sigma_{dP_o}(t)} e^{-\frac{[dP_o - \mu_{dP_o}(t)]^2}{2\sigma^2_{dP_o}(t)}}, \tag{3}$$

$f_G(dP_o)$ is a probability density function. The parameters of the distribution (mean $\mu_{dP_o}(t)$ and standard deviation $\sigma_{dP_o}(t)$) are computed from the real signal $dP_o(t)$.

2.3 Probabilistic model of $T(t)$

The forced power unit outages $T(t)$ are modelled by the Markov process with two states (see Fig. 1) Maslo and Vnoucek [2000], Billinton and Li [2004].

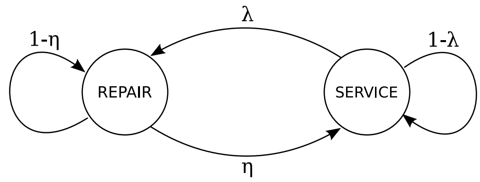

Fig. 1. State diagram of Markov process

The transient rates are given by the relations:

$$\lambda = \frac{1}{MTTF},\ \eta = \frac{1}{MTR}, \tag{4}$$

$MTTF$, MTR are mean times between failures and of repairs. The mean times are obtained through statistical processing of given times between failures and of repairs for particular units. The model is described by the equations:

$$\frac{d}{dt}\begin{bmatrix} p_s(t) \\ p_r(t) \end{bmatrix} = \begin{bmatrix} -\lambda & \eta \\ \lambda & -\eta \end{bmatrix}\begin{bmatrix} p_s(t) \\ p_r(t) \end{bmatrix},\ p_s(t) + p_r(t) = 1, \tag{5}$$

$p_s(t)$ is a service probability and $p_r(t)$ a repair probability.

The forced outages are mostly caused by mechanical failures (e.g. seizure, leakage, etc.) Therefore, dependencies among co-temporary outages are not considered in the model. Partial outages are not taken into account either because they are not frequent, their durations are usually short and amplitudes small. This means that they do not have any substantial effect on the reliability of the system. Modelled power units inhere in the bottom of the tub characteristic with respect to their life cycles. This means that the failure and repair rates are about constant. Thus, the Markov process is precise enough for the modelling.

2.4 Probabilistic model of $dP_{ot}(t)$ and $R(t)$ determination

Consequently, the probabilistic models of $dP_o(t)$ and $T(t)$ are aggregated into a model of the power balance deviation in the open loop mode $dP_{ot}(t)$ that is described by the Gaussian sum Sorenson and Alspach [1971], Alspach and Sorenson [1972] with the probability density function:

$$f_{G_s}(dP_{ot}) = \sum_i \frac{P_i(t)}{\sqrt{2\pi}\sigma_{dP_o}(t)} e^{-\frac{[dP_{ot} - \mu_{dP_o}(t) - T_i]^2}{2\sigma^2_{dP_o}(t)}}, \tag{6}$$

$P_i(t)$ are probabilities of the outages and all their possible combinations and T_i are appropriate amplitudes. The sum is used for determination of the overall positive and negative volumes of ancillary services $R^+(t)$, $R^-(t)$ under a required reliability level of the system operation. The level is given as a percentage share of $dP_{ct}(t)$ amplitudes larger than $\pm 100MW$ along all of its possibly existing amplitudes (the share is called as **Value at Risk** – VaR):

$$R^+(t) = F_{G_s}(1 - \frac{VaR}{2}),\ R^-(t) = F_{G_s}(\frac{VaR}{2}). \tag{7}$$

Since an analytical formula of a cumulative distribution function of the Gaussian sum F_{G_s} is not known, $R^+(t)$ and $R^-(t)$ have to be computed by a numerical algorithm.

2.5 Decomposition of $R(t)$ and economical optimization

The volumes are then divided into power reserves of particular ancillary services on behalf of statistical and dynamical characters of specific components involved in $dP_{ot}(t)$ that should be decayed by corresponding types of the services (a random component $\Rightarrow$ secondary frequency and power control, a direct-energetic component $\Rightarrow$ tertiary control, a forced outage $\Rightarrow$ quick-start, a long-time power imbalance $\Rightarrow$ non-spinning stand-by reserve, emergency assistance, control energy purchase).

Finally, the power reserves are economically optimized. The reserves are re-disposed by the optimization in such a way that the required reliability level (VaR) is kept and costs to their purchase are minimized at the same time.

In order to make sure that the whole optimization procedure of the system operation planning is well done, the Monte-Carlo simulator is employed to verify that the power reserves are large enough for guaranteeing the required reliability level of the system operation.

3. BASIC PARTS OF MONTE-CARLO SIMULATOR

The simulator is composed of the following basic parts:

- **Model of Open Loop:**
  - · model of undisturbed system operation
  - · model of forced power unit outages
- **Model of Feedback:**
  - · model of primary frequency control
  - · model of secondary frequency and power control
  - · model of tertiary control
  - · model of quick-start
  - · model of non-spinning stand-by reserve
  - · model of emergency assistance
  - · model of control energy purchase

All the models are dynamical and represent particular parts of the simulator. Another part of the simulator is a visualization section that enables to view simulated signals in figures. However, this section is not very interesting under consideration the interest of the paper. Therefore, it will not be described at large here.

4. MODEL OF OPEN LOOP

The model of the system operation in the open loop mode (with no control actions) includes two modules: a model of the undisturbed system operation and of the forced power unit outages (see Fig. 2). They are formed in parallel and their outputs are added. The aggregated deviation $dP_{ot}(t)$ is the input of the feedback part of the simulator where it is eliminated by ancillary services employment.

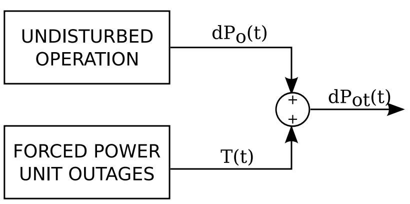

Fig. 2. Model of open loop

4.1 Model of undisturbed system operation

The model is considered as a stochastic linear dynamical system Chen and Hsu [1995], Arnold [1998] that generates a dynamical course of $dP_o(t)$. The deviation characterizes behavior of the system under the assumption that any forced power unit outages do not happen. The model is described by the equations:

$$e(t)=X(t)+a_1X(t-1)+a_2X(t-2)+a_3X(t-3) \quad (8)$$

$$dP_o(t)=X(t)+\mu_{dP_o}(t), \quad (9)$$

$e(t) \sim N\{0, \sigma_{dP_o}(t)\}$ is a Gaussian white noise, $\sigma_{dP_o}(t)$ is a standard deviation of $dP_o(t)$, $\mu_{dP_o}(t)$ is a mean of $dP_o(t)$ and $X(t)$ is an inner state variable. The parameters $\mu_{dP_o}(t)$ and $\sigma_{dP_o}(t)$ are computed from the real signal $dP_o(t)$. The coefficients a_1, a_2 and a_3 are obtained as the output an identification procedure available in the identification toolbox of MATLAB whose input is just the signal $dP_o(t)$. The third-order structure of the model is derived from analyzing the dynamical character of the signal $dP_o(t)$. There is provided the comparison of possible real and modelled realizations of $dP_o(t)$ in Fig. 3.

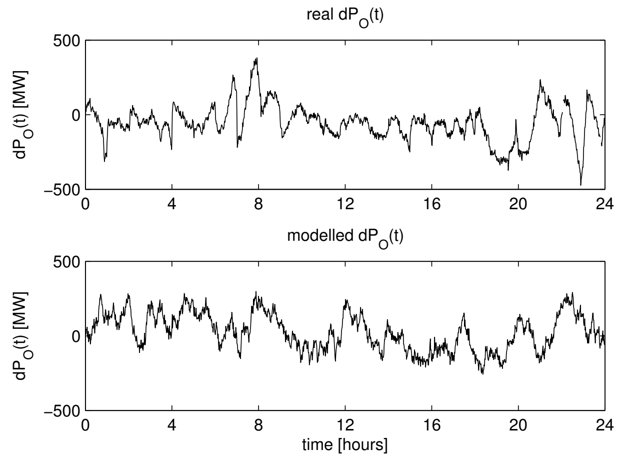

Fig. 3. Comparison of real and modelled courses of $dP_o(t)$

It is obvious that the courses correspond to each other from the dynamical point of view. Another important fact is that both the signals have the same statistical characteristics (mean, standard deviation and correlations).

4.2 Model of forced power unit outages

The dynamical model of the forced power unit outages consists of two random variable generators that produce transient times between its two states (service and repair). The generators are defined by the exponential probability distribution and their parameters (mean times) are computed from statistical processing of times between failures and of repairs for modelled power units. A possible realization of the outages is depicted in the above graph of Fig. 4. You can see the co-temporary outage of two $200MW$ power units, the two single outages of two $200MW$ power units and the single outage of a $1000MW$ power unit. The below graph shows a possible realization of $dP_{ot}(t)$ – the aggregated output of the dynamical models of $dP_o(t)$ and $T(t)$ (Fig. 2) entering the feedback part.

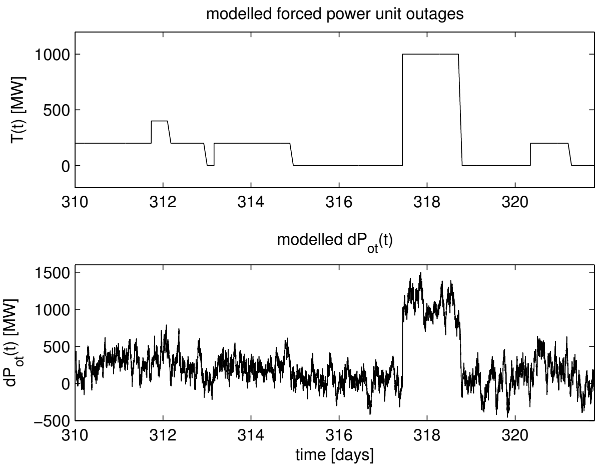

Fig. 4. Courses of $T(t)$ and $dP_{ot}(t)$

5. MODEL OF FEEDBACK

The feedback part of the simulator consists of dynamical models of seven ancillary services – primary frequency control (PC), secondary frequency and power control (SC), tertiary control (TC), quick-start (QS), non-spinning stand-by reserve (NSR), emergency assistance (EA) and control energy purchase (CE) (see Fig. 5).

The first two types of the services work automatically in the closed loop mode. On the other hand, the others are employed by a dispatcher under actual situations in the electricity transmission system (power shortage/excess). The models of the other services have two parts.

The first one generates activations/deactivations and setpoints of a service through fuzzy IF-THEN statements that imitate decisions of the dispatcher under the situations in the system. Then the second part, which follows the first one, models trends of start-ups and shut-downs of the service. More precisely, it implements trends of power units where the service is allocated. The units provide the service through required changes of their output power (activations/deactivations and setpoints of the service).

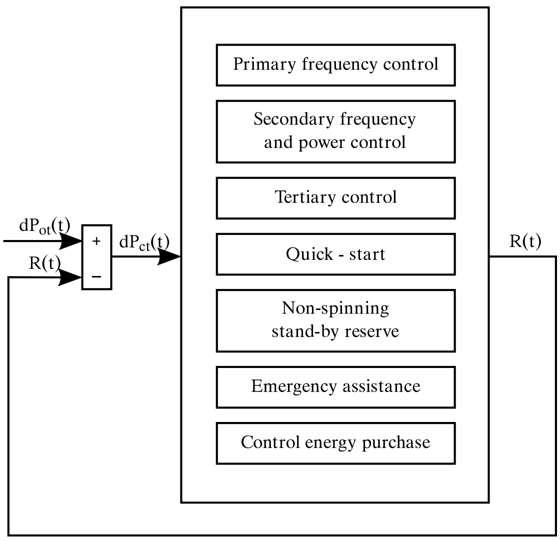

Fig. 5. Model of feedback

5.1 Primary frequency control

This type of control is proceeded by frequency compensators that are included as parts of power controllers of power units. The input of the compensator is a frequency deviation $\Delta f(t)$ in the system and the output is a power deviation $\Delta P_c(t)$ that modifies a setpoint of the power controller. When $\Delta f(t) > 0$ then $\Delta P_c(t) > 0$ and power of the unit is increased. On the contrary, when $\Delta f(t) < 0$ then $\Delta P_c(t) < 0$ and the power of the unit is decreased. The compensator is of P (proportional) type:

$$\Delta P_c(t) = K_c \Delta f(t), \tag{10}$$

K_c is a given gain of the compensator. In order to model the primary control in the simulator, the frequency deviation $\Delta f(t)$ is firstly derived from $dP_{ct}(t)$. Whereas the deviation is the same in the whole interconnected electricity transmission system under the assumption of steady-state operation (i.e. after electromechanical processes vanishing), the deviation is computed as follows:

$$\Delta f(t) = \frac{dP_{ct}(t)}{K_{UCTE}}, \tag{11}$$

K_{UCTE} is a given characteristic power number of UCTE. The model of the primary control is then given by the equation of P controller (see Fig. 6):

$$\Delta P_f(t) = K_f \Delta f(t), \tag{12}$$

K_f is a given primary frequency control droop of the electricity transmission system of the Czech Republic (sum of all the gains K_c of all frequency compensators) and $\Delta P_f(t)$ is a power deviation that modifies the input of an actuator of secondary frequency and power control. The variables $PRPC^+(t)$ and $PRPC^-(t)$ are the power reserve constraints of the primary control given by UCTE:

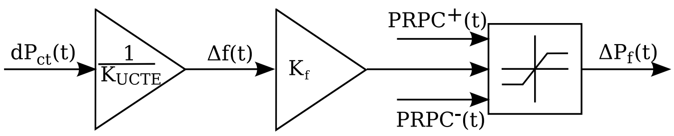

Fig. 6. Model of primary frequency control

5.2 Secondary frequency and power control

The secondary control follows the primary control. It is carried out by a central secondary controller that is found in the dispatching center of the Czech TSO. Its input is a signal denoted as ACE (Area Control Error) defined by the relation:

$$ACE(t) = K_s \Delta f(t) + dP_{ct}(t), \tag{13}$$

K_s is a given secondary frequency and power control droop of the electricity transmission system of the Czech Republic. The output of the controller is a total secondary power setpoint sent in parts to power controllers of the power units where this type of ancillary service is allocated. The units then respond to the parts of the setpoint by changing their output power. It is obvious from (13) that the secondary control suppressed the frequency deviation $\Delta f(t)$ as well as the power deviation $dP_{ct}(t)$ in the system.

The secondary controller is depicted in Fig. 7. It is shown in the figure that $ACE(t)$ is foremost filtered by a filter. Then it inputs a controller that generates the setpoint. The filter is of first-order with a given time constant T_f:

$$F_s(z) = \frac{1}{T_f z + 1 - T_f}. \tag{14}$$

The controller, which follows the filter, is of PI (proportional-integral) type with the anti-wind up effect:

$$F_{pi}(z) = \frac{K_p z + K_i - K_p}{z - 1}, \tag{15}$$

K_p is a given proportional gain and K_i is a given integral constant. The scheme of the controller is shown in Fig. 8. The variables $PRSC^+(t)$ and $PRSC^-(t)$ are the power reserve constraints of the secondary control that result from the optimization procedure described above.

The setpoint generated by the controller is then sent to the actuator of the secondary control foremost modified by the output of the primary control. The actuator models dynamical changes of output power of power units under the setpoints received by their power controllers from the dispatching center. The model of the actuator was identified on the basis of the measured output signal of the controller (input of actuator) and secondary power provided by power units employed by this type of ancillary service (output of actuator). The model was derived as the first-order filter with a given time constant T_a:

$$F_a(z) = \frac{1}{T_a z + 1 - T_a}. \tag{16}$$

This result fully conforms to reality because output power of the power units is changed along a monotonous curve with a certain time constant that corresponds to the step response of a closed control loop including a power unit with its power controller (usually of PI type).

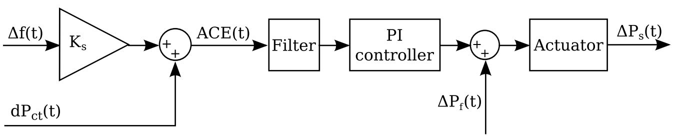

Fig. 7. Model of secondary frequency and power control

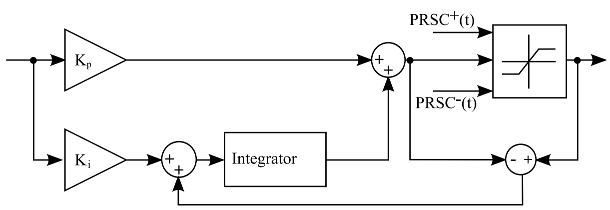

Fig. 8. Model of PI controller with anti-wind up effect

5.3 Tertiary control

This type of ancillary service does not work automatically in the closed loop mode. It is employed by a dispatcher under actual situations in the system. The service is mainly used for de-saturation of the secondary control. In other words, when the secondary control is invoked too much (i.e. it seems that it will early reach the limits $PRSC^+(t)$ or $PRSC^-(t)$), the tertiary control is activated in order to decrease usage of the secondary control. The service is allocated on the same types of power units as the secondary control (mostly steam ones). They respond to activations/deactivations and setpoints of the service by changing their output power along a given trend.

Decisions of the dispatcher, whether to activate/deactivate the service and what value of the setpoint to choose taking into account the power reserve constraints of the service $PRTC^+(t)$ and $PRTC^-(t)$, are modelled by fuzzy IF-THEN statements. The setpoint is then sent to the model that implements the trend δ of the service (see Fig. 9).

5.4 Quick-start

The ancillary service quick-start is entirely allocated on pumped-storage power units that can proceed very sharp trends. The reason is that the service is mainly used for elimination of large and unexpected power imbalances (e.g. forced power unit outages) that have to be decayed in a very short time because of frequency recovery.

Unfortunately, efficiency of the service is limited by capacity of water reservoirs of the power stations whose power units are employed by this service. Therefore, it has to be replaced after a while by activating other types of ancillary services (non-spinning stand-by reserve, emergency assistance, control energy purchase) when activated.

Operation of quick-start is modelled by fuzzy IF-THEN statements again considering the power reserve constraint of the service $PRQS^+(t)$. The model of the trend is the same as in case of the tertiary control (δ is only different). By the way, all the other services that will follow are modelled in the same way as the tertiary control and quick-start. The difference is only in various fuzzy IF-THEN statements, values of power reserve constraints and trends.

5.5 Non-spinning stand-by reserve

This is an ancillary service used for replacement of quick-start when activated. The service is mostly allocated on gas, steam-gas power units that are found in the reserve shutdown state waiting for activation by a dispatcher.

5.6 Emergency assistance and control energy purchase

These two ancillary services are delivered from abroad. Activations of the first one (emergency assistance) are arranged between two TSOs (usually neighboring). The activation is then proceeded in such a way that a value of cross-border power balance is changed (import of power is increased in a required setpoint along a certain trend).

The other service (control energy purchase) is bought at an international electricity market by a trade department of the Czech TSO when needed. The activation is then performed in the same way as in case of the emergency assistance (power import is increased).

Unfortunately, these two ancillary services are not always available when wanted. This fact is also modelled in the simulator, of course, as a given parameter (probability) that expresses a level of their availability.

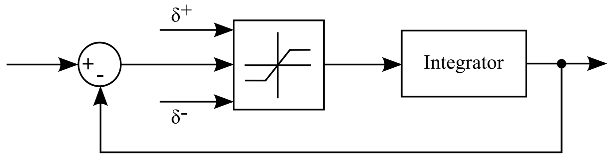

Fig. 9. Model of service trend

6. ILLUSTRATIVE EXAMPLES

The functionality of the simulator is demonstrated at Fig. 10, 11. The first three graphs (Fig. 10) shows a realization of undisturbed system operation. You can see that the secondary and tertiary control are only employed. The other three graphs (Fig. 11) present a process of elimination of the $1000MW$ forced power unit outage.

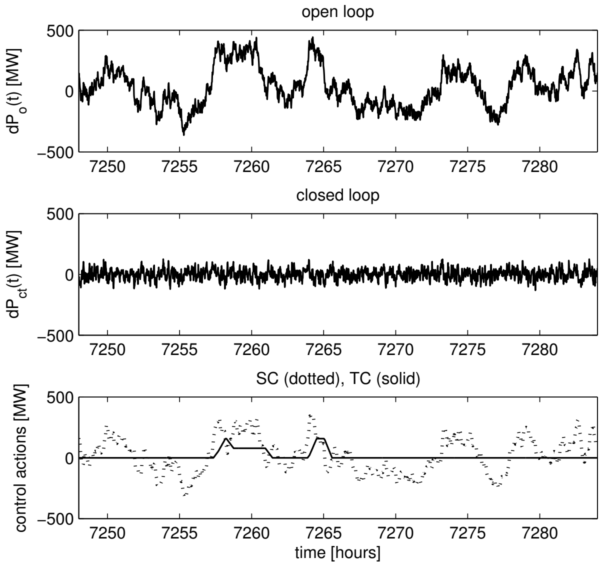

Fig. 10. Realization of undisturbed system operation

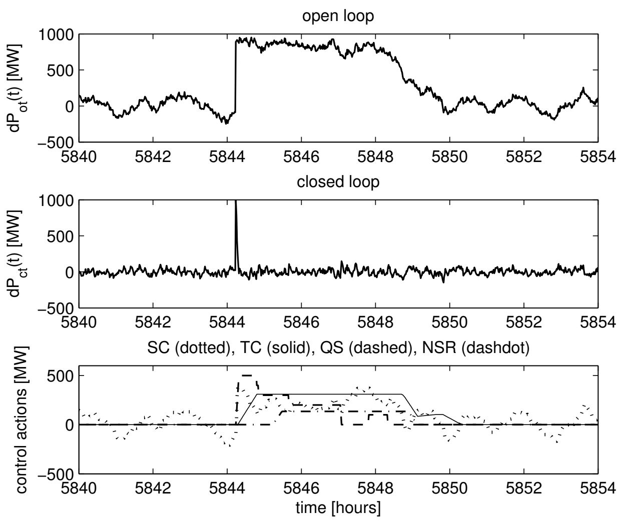

Fig. 11. Process of $1000MW$ forced outage elimination

7. CONCLUSION

The presented simulator, which models and simulates electricity transmission system operation, serves the Czech TSO to verify whether the economically optimized power reserves of the ancillary services are large enough for guaranteing a required reliability level of the system operation.

The parameters of the models involved in the simulator (probabilities of forced outages, means, standard deviations, power reserve constraints, etc.) are time-varying. This means that their values can be changed within a planning period (e.g. year, month, etc.) catching on behavior of the system at specific stages (e.g. seasons, etc.).

The simulations are started from random initial conditions. Therefore, it is quite useful to perform sufficient number of simulations in order to cover all possibilities that could happen. For this purpose, the simulator contains a function that recommends appropriate number of simulations under a required width of confidence interval and a percentage value of significance level.

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