Impact of Magnetically Controlled Shunt Reactors on Transient Stability of Oil-Production Enterprise Isolated Power Systems

A. N. Belyaev, *Member, IEEE*, and S. V. Smolovik, *Member, IEEE*

***Abstract* -- Oil- and gas-production enterprises are large and heavy-duty power consumers. The highest priority in design of new oil-field power supply systems should be devoted to ensuring uninterrupted, reliable and qualitative electric power generation as well as system survivability under variety of unpredictable incidents. The paper is primarily concerned with analyzing alternatives of preventive control in isolated oil-field power system. As the main reason of severe accidents in isolated oil-field power systems is voltage collapse and induction motor shutdown, it should be considered to install reactive power compensation facilities at the most critical load buses. The results of isolated power system transient analysis show that application of this combined unit allows to enhance dynamic stability at least to 50%.**

***Index Terms* -- induction motors, oil industry, reactive power control, transient stability, voltage collapse.**

I. Introduction

OIL- and gas-production enterprises are large and heavy-duty power consumers. It is specific for operators in regions such as West Siberia to be weakly bound complex over great territories with severe climatic conditions possessing wide range of various electrical facilities. New oil and gas field developments are stimulated by high fuel world market price level, scientific and technological achievements in reservoir engineering and exploration as well as quality of reasonably assured resources.

Interruption of the electric power supply, in particular during oil extraction process, tend to result in disorderly closedown in a matter of seconds after emergency with further system restoration not earlier than one or two hours or even a few days in a limited number of cases. Therefore, the highest priority in design of new oil-field power supply systems, which, on numerous occasions, are isolated, should be devoted to ensuring uninterrupted, reliable and qualitative electric power generation as well as system survivability under variety of unpredictable incidents. It is also well known, that power interruptions during exploration drilling could entail much worse consequences.

In-depth analysis of some new oil-field power grid particular characteristics as well as potential scenarios of dangerous disturbances indicates the demand of countermeasure package designed to protect power system against blackouts and to offer permissible power quality level. This emergency plan must among other issues include the requirements to automatic protection for entire system to prevent from prohibitive drop or growth of frequency (and/or voltage), to enhance the stability of gas turbine or gas reciprocating units, generators, synchronous and induction motors, to avert the equipment overloading.

The paper is primarily concerned with analyzing alternatives of preventive control in isolated oil-field power system (Fig. 1) during three-phase short circuit at high-voltage side of power plant and subsequent tripping half of generation and transmission lines (normally every component of oil production is supplied by 110 kV double-circuit line).

Magnetically controlled shunt reactors (MCSR) are the perspective devices for reactive power shunt compensation in not only EHV long-distance transmission lines [1]. Using CSR allows

- to control maintenance of voltage or any other operation parameter without using circuit breakers in automatic switching systems;
- to decrease active power losses in networks and to improve their operational reliability by reducing the number of switching in on-load tap-changing transformers;
- to enlarge small signal stability margin;
- to improve power system damping;
- to minimize using of synchronous generators as a controlled sources of reactive power.

II. Power System Modeling

The distinguishing features of oil-field power systems are the following

- the isolated operation without any connection to national power grid;
- the arrangement of gas-turbine or gas reciprocating units (with total capacity up to 250 MW) in the center of field with radial power supply from at least two 110 kV substations, which are distanced from power plant not more than 20 km [3];
- the nomenclature of power consumers, which consist around 80% of motor load included heavy synchronous

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motors, which are 40% of the field rated load.

The most expected operating emergency conditions of oil-field auxiliary power supply are as follows

- considerable load dropping of gas-turbine units (by amount of 25-35% unit rated power) after nearby fault in 110 kV power grid;
- sudden load surge on one bus section of gas-turbine power plant up to 25% of unit rated power after blackout of parallel section.

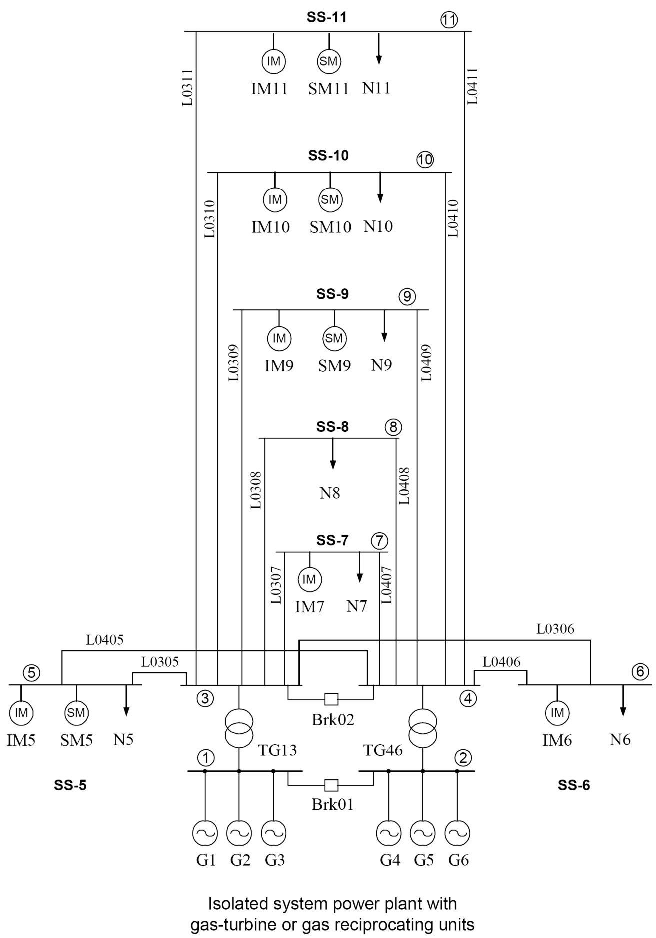


Fig. 1. Simplified model of isolated oil-field power system.

The variations of simplified model, presented in Fig. 1, may only concern primary connections of power plant, but general principles of motor load power supply remain invariant. Total capacity of units is from 50 to 200 MW.

High maneuverability of plant units is, in most cases, negative feature from transient stability point of view, since the value of turbogenerator mechanical inertia constant decreases down to $H_J = 2$ sec. E.g., gas reciprocating unit with following characteristics – total capacity 10,913 MW, rotor speed 750 rpm, generator and turbine inertia 2,150 and 1,070 kg·m^2, respectively, has inertia constant value

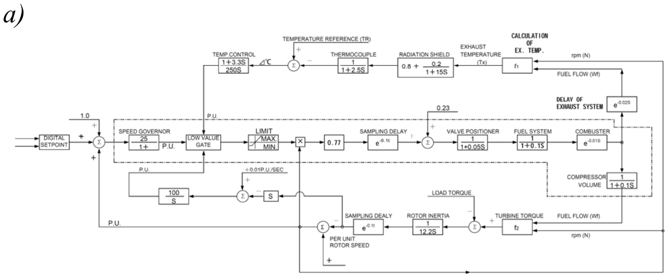
$$H_J = 4 \cdot \frac{2{,}74 \cdot GD^2[t \cdot m^2] \cdot n^2[rpm]}{S_{ном}[kW]} \cdot 10^{-3}[\text{sec.}] =$$

$$= 4 \cdot \frac{2{,}74 \cdot (2{,}150 + 1{,}070)[t \cdot m^2] \cdot 750^2[rpm]}{10913[kW]} \cdot 10^{-3} = 1{,}819 \text{ sec}.$$

Qualitative combination of power consumers in oil-field isolated networks may dramatically differ from the same indices of bulk power system. In particular, total share of motor load could reach 95% (about 55% of induction motors and 40% of synchronous ones). While small signal stability limits are many times as large as active power flows in normal operations, the quantity indices of transient stability, such as critical fault clearance time, could be lower than standard levels. Acceleration of generators and slowdown of synchronous motors during severe accident, e.g. two- or three-phase short circuit at high-voltage side of power plant, could cause the loss of synchronism between them much faster than the shortest tripping time of modern switchgear is.

The modeling of gas turbine units is conventionally based on ASME diagrams [3]. In addition to it, the experience of transient stability calculations in isolated power systems with gas turbine units shows that reference model (Fig. 2, *a*) could be substantially simplified to the scheme, which is represented in Fig. 2, *b*. This control loop can be introduced as basic governor for parallel operation with national power grid.

a)



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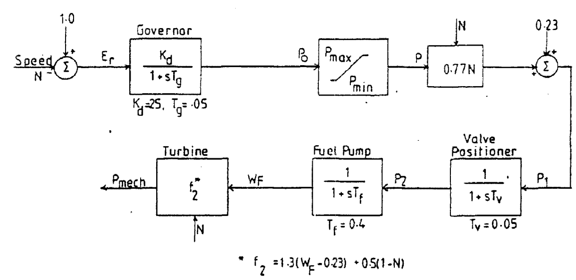


Fig. 2. Detailed (a) and simplified (b) gas turbine model [3, 4].

III. Transient Stability of Isolated Power Systems

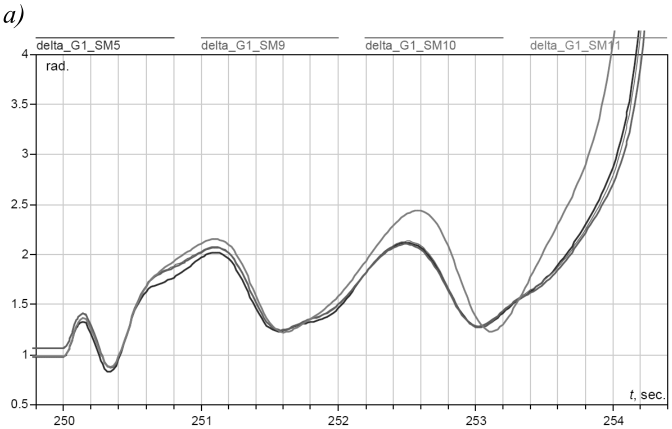
Fig. 3 illustrates the second emergency condition by calculating transient-response curves of system variables. The normal operation is very far from stability limits considering the power flows transmitted by unaffected lines, while system collapses due to its load (around 80% of induction and synchronous motors) behavior.

The first swing of mutual angles (Fig. 3, *a*) is relatively small, since active power shortage is reasonably fast compensated by the action of gas-turbine or gas-reciprocating unit speed governors. However, load bus voltages are significantly reduced in post-fault operation (Fig. 3, *b*). In addition to it, the increase of active power flow through transmission lines remaining in operation cause additional complications when voltage will drop at a yet faster speed.

Finally, electrical torque characteristic will fall below mechanical one (Fig. 3, *d*) with subsequent voltage collapse [4, 5]. The rotor speed of induction motors (Fig. 3, *c*) will slow down with increasing reactive power consumption and engine shutdown. Synchronous motors are also involved in process even though their automatic regulators are not able to maintain load bus voltages in a proper way, that is why after some swings they will slow down as well. It leads to transient instability in terms of mutual rotor angle motion between power plant generators and oil-production synchronous motors.

In some cases the operation of oil-field power system model becomes unstable when critical fault clearance time is less than or equal to 0,03 sec. At the same time, modern protective gear can isolate the fault from the running system for 0,06-0,1 sec. It is simply evident that there is no equipment to clear faults for the time to be specified.

a)



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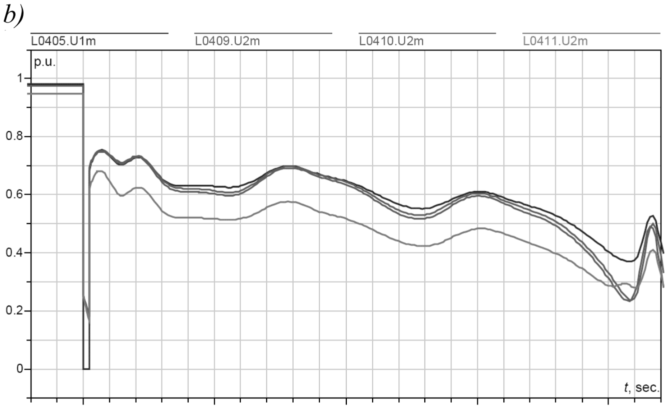

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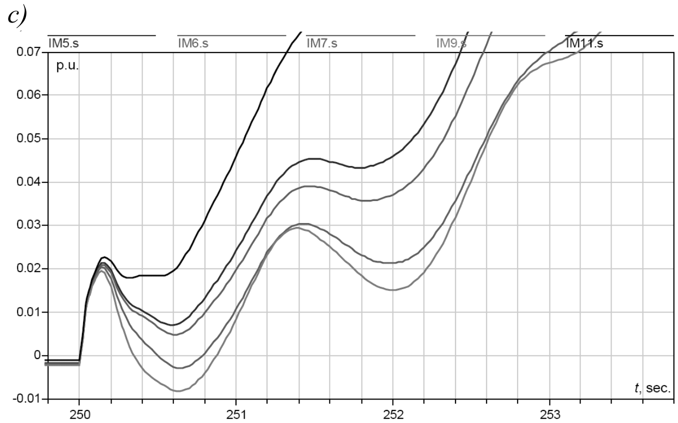


d)

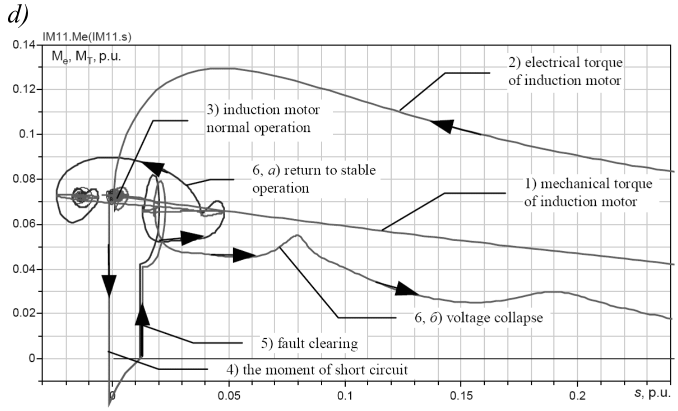


Fig. 3. Electromechanical transients following 0,04 sec. three-phase short circuit at power plant bus section with tripping off the half of generating units and transmission lines

a) mutual angles between rotors of generators and equivalent synchronous motors; b) power plant and load bus voltages; c) relative rotor speed variation of induction motors; d) experimental power/speed characteristics of equivalent induction motor (function of mechanical and electrical torques from rotor speed variation) at load bus, derived from transient calculations.

Analysis of possible unstable operation of equivalent induction motors and subsequent voltage collapse can be performed in the most intuitive way by drawing experimental power/speed curves for equivalent induction motors derived from electromechanical transient calculations (Fig. 3, *d*). In general there is the family of curves for each induction motor for operation on various supply voltage. Induction motor is supposed to connect to infinite bus which means that motor capacity is much less than power system one. However, voltages at load buses fluctuate intensively in isolated power systems especially in post-fault operations. The root cause of this oscillations is high level of reactive power consumption by induction motor itself. Then electrical torque characteristic is severely reduced even lower than mechanical one. Long-duration negative power imbalance leads to induction motor shutdown. Therefore strong voltage control at critical induction motor load buses is of primary concern to ensure system survivability in post-fault operations.

IV. Application of Controlled Shunt Reactors in Oil-Production Enterprises

It is repeatedly shown [1, 5, 6], that implementation of controllable shunt compensation devices at 500 kV long-distance transmission systems does not much influence on mutual angles between generators and transient stability, since such an interaction is defined on excitation and active power control systems of generators themselves. But voltage behavior at intermediate points of transmission systems depends primarily on performance of shunt compensation device, especially in post-fault operations.

The magnetically controlled shunt reactor (MCSR) is a three-phase powerful extension of magnetic amplifier with inverse-parallel connection of control windings (Fig. 4), which allows to decrease the power of these windings considerably (by the factor of 100÷1000). The MCSR has steel magnetic core with the main winding (UHV) and control one (UC). The latter is fed by power electronics controlled rectifier providing variable DC superposed magnetization current. In terms of small disturbance stability, it means the increment of MCSR equivalent time constant T_p (up to 3-4 sec.). At the same time, it can be decreased in special cases by application of magnetic field forcing for short period down to T_p = 0,1 sec. When control voltage is equal to zero reactor stays in one of the fixed operating modes, for instance idling (I), rated load (II), rated overload (III). Increasing or decreasing of the phase current is accomplished by corresponding change of the control voltage U_C.

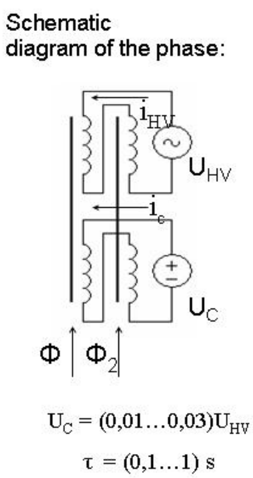


Fig. 4. Operation principles of MCSR.

As the main reason of severe accidents in isolated oil-field power systems is voltage collapse and induction motor shutdown, it should be considered to install relatively simple, generally accepted reactive power compensation facilities (e.g., controlled shunt reactor with conventional capacitor bank) at the most critical load buses.

The rated reactive power of capacitor bank (BC) and CSR is assumed to be 0,2 and 0,1 p.u., respectively, which means that in normal operation reactive power will be generated at the level of 0,1 p.u. keeping the control range from 0 to 0,2 p.u.

Generally, mathematical description of CSR control law for small signal stability investigations can be expressed as follows

$$\left(1+pT_p\right)\cdot b_p = b_{p0} + k_{0u}\Delta U_p,$$

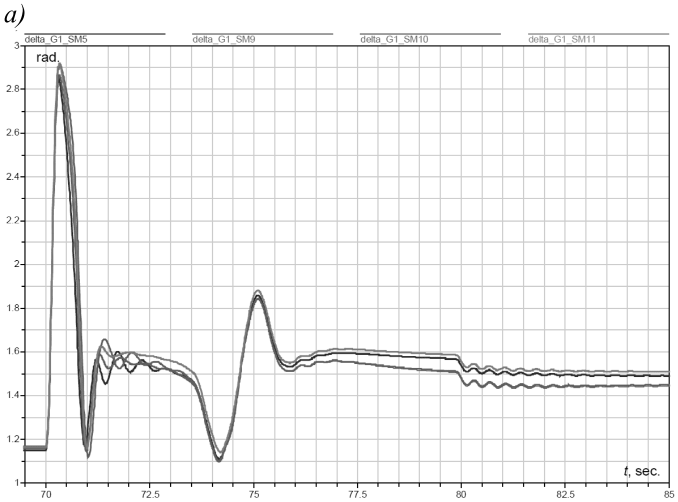
where b_p and b_{p0} – are actual and initial (at predetermined operation) CSR conductivity; k_{0u} – terminal voltage deviation ΔU_p control gain; T_p – equivalent time constant of CSR control system.

The joint operation characteristics of CSR + BC installation at the most critical load buses should be taken from small signal and transient stability calculations. For example, CSR voltage references are equal to 0,98 p.u. delivering the natural voltage drop on short transmission lines as well as remaining values of mutual angles between synchronous generators and motors in previous operating conditions (without CSR + BC). The control gains of terminal voltage deviation are supposed to be the same as in generators and motors (k_{0u} = -25) to maintain the voltage level at load buses in proper way.

The equivalent response of CSR control system can be varied (moreover, it could be different when modeling reactive power increase or drop) in wide range (T_p = 0,1÷1 sec.). However, it can be shown that long-term post-fault fluctuations is appeared when T_p is quite small. For that reason, it is highly recommended to install CSR with quite considerable value of control system response (T_p = 1 sec.).

The results of isolated power system transient analysis (Fig. 5) show that application of this combined unit (reactor + bank) allows to enhance dynamic stability, i.e. to increase permissible short circuit duration, at least to 50%. Motor shutdowns can be eliminated by stabilizing voltage level at load substations. In this case transient instability may take place with much longer short circuit duration (0,1 sec. instead of 0,04 sec.) which can be tripped off by any modern breaker.

a)



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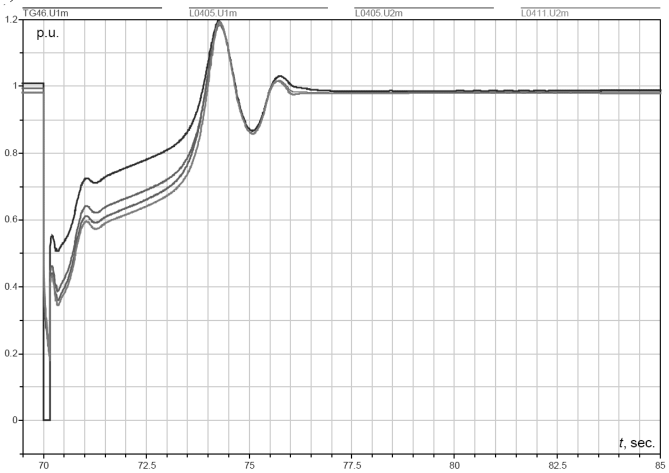

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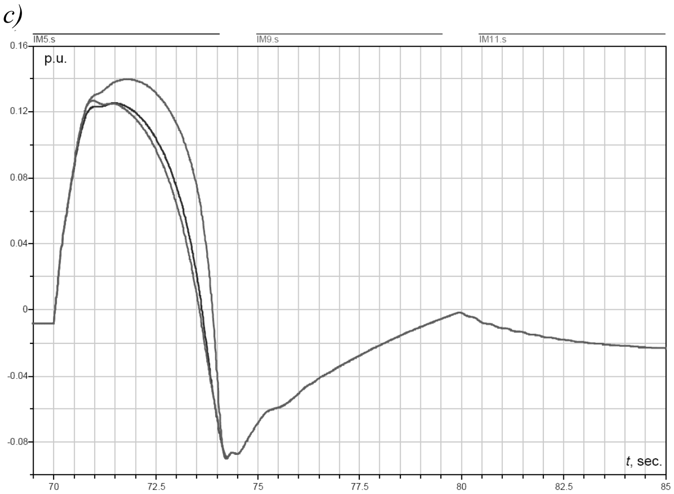

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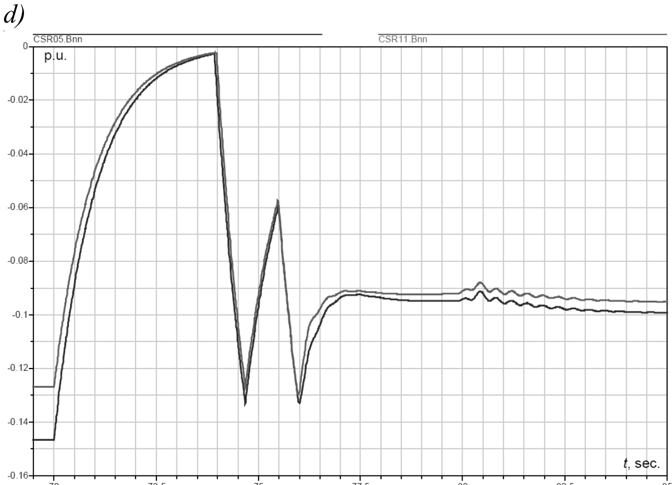

Fig. 5. Electromechanical transients following 0,099 sec. three-phase short circuit at power plant bus section with tripping off the half of generating units and transmission lines

a) mutual angles between rotors of generators and equivalent synchronous motors; b) power plant and load bus voltages; c) relative rotor speed variation of induction motors; d) MCSR response.

V. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

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