

ЭЛЕКТРОТЕХНИЧЕСКИЕ КОМПЛЕКСЫ И СИСТЕМЫ

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THE IMPACT OF USING ELECTRIC ENERGY STORAGES ON THE SYRIAN POWER SYSTEM STABILITY

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In recent years, a real opportunity to create a capacitive-storage energy source based on supercapacitors with increased energy intensity has appeared. At present, on the basis of supercapacitors, an energy storage device (ES) has been created, and there is an experimental process, the power of which in the model of an electric power system is 10 kW. The level of stored energy is determined by the type of storage device (30 kJ or more). The purpose of the paper is to develop effective methods for increasing frequency, rotor angle based on modern energy storage devices (supercapacitors). The program of Power System Simulation for Engineering (PSS/E) is used in the study. The importance of the work is described in the paper and the features of the impact of using supercapacitors on the stability of frequency and rotor angle by making several experiments with different capacities and voltages and then comparing the results obtained using the PSS/E program are considered. Ensuring the stability of the load schedule at the maximum consumption of electricity in the electric power system of a certain region or country is a long-term procedure that needs to be developed and improved in the means of its implementation. Modern systems have characteristic features, such as an increase in the unevenness of load schedules, the need to generate power from generation facilities in each period of time, an increase in the steepness of load schedules, scaling of power plant equipment, which increase their economic feasibility of operation, reduce their maneuverability, etc. Search and development of new ways and methods for compensating peak loads in the electric power system are relevant and in demand.

Keywords: supercapacitors, energy storage, stability, rotor angle, frequency, capacity, battery, charge, discharge, interconnection.

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ВЛИЯНИЕ ИСПОЛЬЗОВАНИЯ НАКОПИТЕЛЕЙ ЭЛЕКТРОЭНЕРГИИ НА УСТОЙЧИВОСТЬ СИРИЙСКОЙ ЭНЕРГЕТИЧЕСКОЙ СИСТЕМЫ

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Ввиду того, что в последние годы появилась реальная возможность создания емкостно-накопительного источника энергии на основе суперконденсаторов с повышенной энергоемкостью, в настоящее время на основе суперконденсаторов создано устройство накопления энергии и имеется экспериментальный процесс, мощность которого в модели электроэнергетической системы составляет 10 кВт. Уровень запасаемой энергии определяется типом накопителя 30 кДж и более. Целью данной статьи является разработка эффективных методов повышения (частоты, угла ротора) на основе современных накопителей энергии (суперконденсаторов). В ходе проведения теоретических и экспериментальных исследований применена лицензированная программа математического моделирования электроэнергетической системы (ЭЭС) — PSS/E. В статье обоснована практическая важность научной работы и рассмотрены особенности влияния использования суперконденсаторов в целях обеспечения стабильности частоты вращения и угла ротора посредством проведения нескольких экспериментов с различной емкостью и напряжением и с последующим сравнением с результатами, полученными с помощью программы (PSS/E). Обеспечение стабильности графика нагрузки при максимальном потреблении электроэнергии в электроэнергетической системе определенного региона или страны является долговременной процедурой, которая нуждается в развитии и совершенствовании средств ее выполнения. Современные системы имеют характерные особенности, такие как рост неравномерности графиков нагрузки, необходимость выработки мощности от объектов генерации в каждый промежуток времени, повышение крутизны графиков нагрузки, масштабирование оборудования электростанций, которое повышает их экономическую целесообразность эксплуатации, снижающее их маневренности и др. Поиск и разработка новых способов и методов компенсации пиковых нагрузок в электроэнергетической системе являются актуальными и востребованными.

Ключевые слова: суперконденсаторы, накопитель энергии, устойчивость, угол нагрузки, частота, емкость, батарея, заряд, разряд, объединение.

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Introduction

The energy storage system is one of the key components of autonomous generation facilities, operating on the basis of hybrid operation between traditional and non-traditional energy sources.

There are various ways to store energy, such as:

1. Mechanical — in the form of converting electrical energy into kinetic energy, returning it when the need for electricity reaches a peak. This method is not widely used in power generation facilities.
2. Hydraulic — in the form of a technological cycle for the operation of a pumped storage power plant. This method is widely used provided there is a large storage reservoir and a source of water resources.
3. Pneumatic — in the form of air compression in cylinders or tanks with high pressure. This method is not widely used in power generation facilities.
4. Electrochemical — in the form of the use of various types of power batteries in wind and solar power plants. This method is widely used in renewable energy facilities, but there is a need for periodic replacement of elements (every 2–3 years), the presence of an enhanced heat supply and ventilation system in order to maintain the optimum temperature inside the room where the system itself is stored.
5. Ionistors — in the form of the use of supercapacitors with increased electrical capacity, characterized by an accelerated charging procedure, a high number of charge-discharge cycles, a high operating temperature range (from -50°C to $+85^{\circ}\text{C}$), etc.

Thus, in the foreseeable future, with a decrease in the cost of production of supercapacitors, their use in energy storage systems in combination with electrochemical energy storage devices is relevant and in demand.

Table 1 provides an overview comparison of a supercapacitor with electrochemical energy storage devices.

Table 1

Comparison of a supercapacitor with electrochemical energy storage devices

Operating parameters	Lead battery	Li-ion battery	Supercapacitor
Density (Wh/kg)	30–40	200	4–12
Operating temperature (°C)	–25; +40	–25; +50	–50; +85
Number of charge-discharge cycles	300	1 000	500 000
Internal resistance (Ω)	3–7	0.39	0.25–0.45
Leakage current (mA)	0.5–1.0	0.2–0.5	1–4
Toxicity	Presence of heavy metals	The presence of harmful substances for water and soil	Low toxicity
Charge time (sec)	from 3 600		to 120
Efficiency (%)	80–90	90–95	95–97

Thus, supercapacitors are better than electrochemical energy storage devices in terms of basic electrical parameters. However, this technology has a high cost. The cost of 1 kWh supercapacitor is about \$10,000, while the cost of 1 kWh Li-ion battery is up to \$1,000. In this regard, the cost of supercapacitors is 10 times higher than Li-ion batteries.

Based on scientific, technical and operational practice, storage devices can be electrochemical capacitors based on the effect of a double electric layer and having a capacity of tens and hundreds of farads at a voltage of approximately 350 V in one module or more [1].

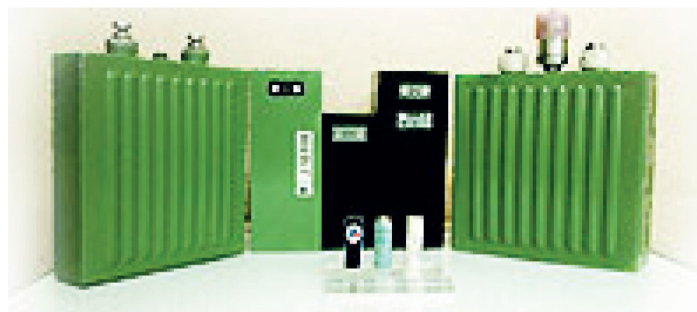


Fig. 1. Modular design of capacitive storage power plant based on supercapacitors CAPACITOR 110 PP-14/0.3

Tests of a powerful electrical complex made it possible to substantiate the requirements for the creation of a sufficiently powerful battery of high-voltage capacitors that can withstand currents of several kA; the energy capacity of the battery can be increased to 1000 MJ [2]. This allows you to solve a number of electrical power problems that can partially or fully satisfy the requirements of the EPS using electrochemical capacitors:

1. Increasing the capacity of interconnection between EPS.
2. Stabilization of frequency and voltage, improving the quality of electricity.
3. Improvement of static and dynamic stability and, general increase in the reliability of the the electrical power system (EPS).

ES can be divided into groups according to three main characteristics nominal power; speed; installation location requirements [3].

ES (supercapacitor) is connected to the excitation system of the synchronous generator through automatic control excitation (ACE) in Fig. 2.

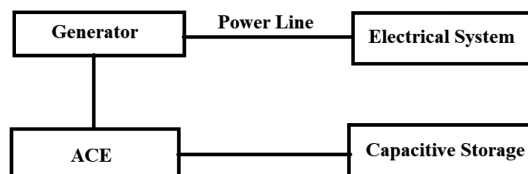


Fig. 2. Diagram of energy storage connection

Due to the fact that the energy storage device is an element of the power system, it must operate both under normal and emergency conditions, so there are several operating modes of the storage device:

1. Energy storage mode (charge): At the same time, the generators at the power plant produce more energy than the consumer requires.
2. Energy output mode (discharge): If the load is greater than the generation of power plants, the drive is discharged and gives the previously accumulated energy to the consumer.
3. Emergency modes: sudden discharges and surges of load, swings, shutdowns of some generators.

At the moment, there are various types of supercapacitors from various manufacturers on the market for electrical products. It is necessary to note the following manufacturers that produce the highest quality supercapacitors for energy storage systems, including for mini- and microgrids: Maxwell, Phoenix, Vishay, Panasonic, Rubycon, Green Tech, ApowerCap, etc.

Existing types of supercapacitors have the following line of electrical capacity: 1; 4; 10; 22; 30; 50; 70; 100; 360 and up to 3640 F. However, the electric capacity of supercapacitor sections can be increased by a certain list of parallel and series connections of these elements.

Methods and Materials

A. The transient processes in the electrical circuit by using electrochemical capacitors:

A supercapacitor is an electrochemical component, and its DC equivalent series resistance r is high. Therefore, manufacturers often choose the value (r) at frequency (1 kHz), which is the minimum. In contrast to a conventional capacitor, in which charge is transferred by electrons, in an electrochemical supercapacitor, ions participate in this process along with electrons. The values C and r of the supercapacitor significantly affect the nature of the time dependence of the voltage. Assume a circuit consisting of a series connection resistor r and capacitor C (Fig. 3).

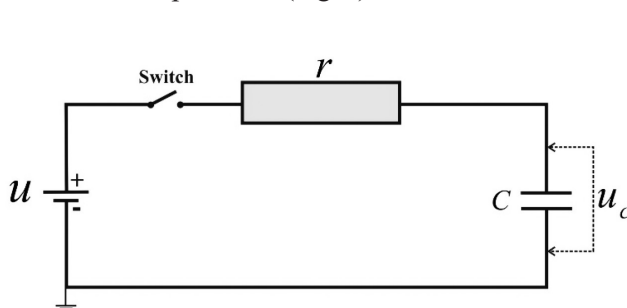


Fig. 3. Resistor-capacitor circuit (RC)

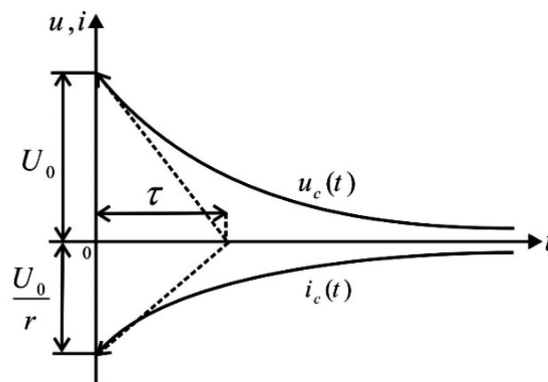


Fig. 4. Transient Response of RC Circuits

If the voltage at the circuit terminals is u , and the voltage at the capacitor plates is u_c and the value of its charge is q , then:

$$ri + u_c = u; \quad (1)$$

$$i = \frac{dq}{dt} = \frac{d(Cu_c)}{dt} = C \frac{du_c}{dt}. \quad (2)$$

Put (2) in (1):

$$rC \frac{du_c}{dt} + u_c = u. \quad (3)$$

The homogeneous equation defining the free voltage u_c'' will be:

$$r \cdot C \cdot \frac{du_c''}{dt} + u_c'' = 0. \quad (4)$$

Its characteristic equation is:

$$rC\alpha + 1 = 0, \quad (5)$$

where

$$\alpha = -\frac{1}{rC}. \quad (6)$$

Therefore,

$$u_c'' = Ae^{-t/rC} = Ae^{-t/\tau} \quad (7)$$

$\tau = rC$ Circuit time constant.

For the transition process we get:

$$u_c = u_c' + u_c'' = u_c' + A \cdot e^{-t/\tau} \quad (8)$$

where the steady-state voltage u_c' can be found if the form r of the function $u(t)$ is known, and the integration constant A is determined from the initial conditions.

When the net voltage drops to zero and let (r, C) be short-circuited, which corresponds to zero voltage.

For a steady voltage on the capacitor $u_c' = 0$, therefore:

$$u_c = u_c'' = Ae^{-t/rC}. \quad (9)$$

Suppose that by the moment of switching, before the short circuit, the voltage on the capacitor was $u_c(-0) = U_0$.

From the condition $u_c(+0) = u_c(-0)$, assuming in the equation $u_c = U_0$ and $t = 0$ we find: $U_0 = A$.

$$u_c = U_0 e^{-t/rC}. \quad (10)$$

The current in the circuit and the energy released in the resistance associated with the capacitance value are determined by:

$$i = C \frac{du_c}{dt} = -\frac{U_0}{r} \cdot e^{-t/rC}. \quad (11)$$

According to the equation, the current at the initial moment changes abruptly from zero to U_0/r :

$$\int_0^{\infty} i^2 r dt = \frac{U_0^2}{r} \int_0^{\infty} e^{-2t/rC} dt = \frac{1}{2} CU_0^2. \quad (12)$$

The energy released in the form of heat in the resistance of the circuit is equal to the energy stored by the electric field of the capacitor at the initial moment of time. An increase in resistance leads to an increase in the time constant of the discharge of the ES, which is preferable for stabilizing the voltage on the consumer's buses [4].

B. Determination of parameters of electrochemical capacitors:

Pulsed energy-intensive capacitors (EC) can solve the problems of a modern EPS. They can be installed almost anywhere in EPS, as well as to equalize load curves and increase stability [5].

From Fig.5 to cover the load schedule in the power system without EC, the required total power of the ES operating in the base part of the load schedule is P_{b1} , in the semi-peak P_{p2} and peak P_{p1} . Let us increase the power from the stations operating in the base part of the load schedule by ΔP_b , since the excess power is generated, which accumulates in the EC.

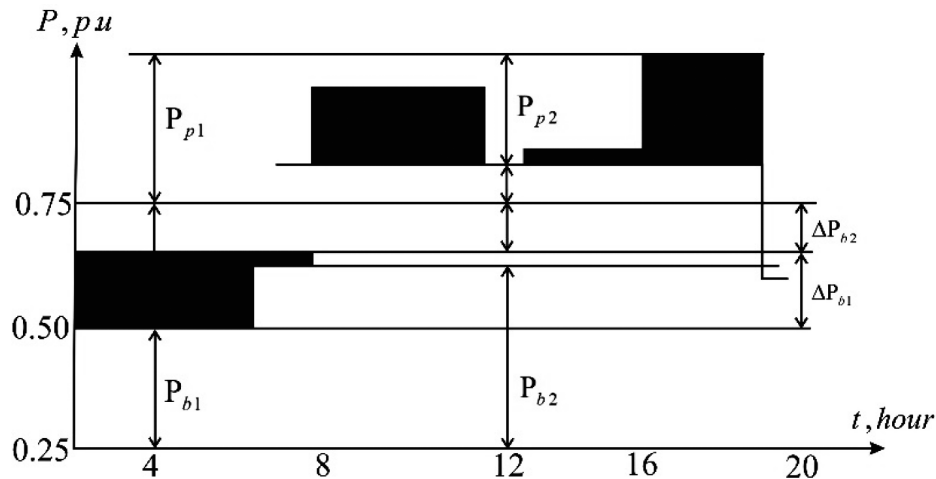


Fig. 5. Graph of the change in the structure of the generating capacities of the EPS when it includes ES of various capacities and energy intensity

The amount of energy received from the EC will be less than the energy received by it from the EPS in the charge mode by the value of losses. Energy losses in the EC for one charge-discharge cycle consist of three components: losses in the charge mode, in the storage mode and in the issuance mode. It should be noted that ΔP_b cannot be chosen arbitrarily. ΔP_b must be a multiple of the power of one of the units installed at stations operating in the base part of the load curve.

The power of semi-peak plants will decrease by ΔP_b , and the power of peak plants will change by P_p for the whole structure of the generating capacities of the system. In this case, the energy intensity of the EC, necessary for leveling the load schedule, will become equal to the excess energy generated by the ES operating in the base mode.

The power of the EC is found from the value of ΔP_b , which determines the maximum power of its charge, and the power it gives out during the passage of the load peak.

The duration of the EC operation in the discharge mode (during the passage of the maximum load) is less than the duration of its operation in the charge mode, therefore the output power is greater than the received one, equal to ΔP_b .

Therefore, the power value of the EC P_p is selected in accordance with the highest power given by it to cover the peak part of the load curve.

The percentage of energy given out by the EC during the dip can be obtained from:

$$\frac{E_{st}}{E_{out}} = \frac{CU_1^2}{2} / \frac{C}{2} [U_1^2 - U_2^2]. \quad (13)$$

E_{st} : Energy stored (J); E_{out} : Energy given off (J); U_2 : Final voltage (V); U_1 : Initial voltage (V); C : Electrical capacitance EC (F), provided that:

$$U_2 = \frac{U_1}{2}. \quad (14)$$

The final discharge voltage corresponds to 50 % of the initial (the most rational), substituting (14) into (13), we get:

$$\frac{E_{sto}}{E_{out}} = \frac{8CU_1^2}{2 \cdot 3CU_1^2} = \frac{4}{3}. \quad (15)$$

Thus, the EC is able to give about 75 % of the accumulated energy when discharged to a level of 50 % of the initial voltage.

The required capacitance of the EC for issuing such an amount of accumulated energy when discharging up to 50 % of the initial voltage is determined from:

$$C = \frac{8 E_{out}}{3 U_1}. \quad (16)$$

Since the EC operates as part of an electrical circuit, it is necessary to take into account the voltage drop on them at the time of energy consumption:

$$\left. \begin{aligned} \Delta U &= Ir; \\ I &= \frac{P}{U}. \end{aligned} \right\} \quad (17)$$

Where:

I: the current circuit (A); r: internal resistance EC (Ω); U: voltage in circuit (V); P: power (W).

Then equation (14) will be written as:

$$U_2 = \frac{U_1 - \Delta U}{2}. \quad (18)$$

One of the main distinguishing features of this system is the ability to regenerate energy from rectifier units during recharging of lead-acid batteries of backup DC sources [6].

C. Experimental study of a combined power plant based on electrochemical capacitors:

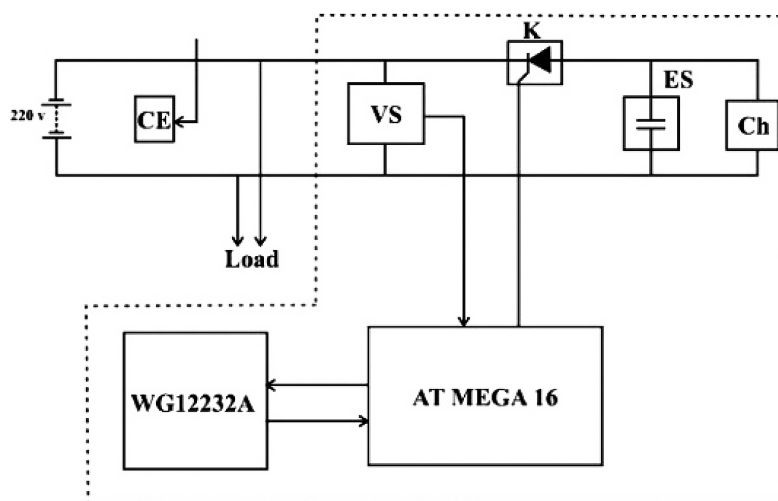


Fig. 6. Diagram of connecting a supercapacitor (ES) to the DC system of a power plant or substation

VS: voltage sensor; CE: control element; Ch: Charger; K: electronic switch; ES: energy storage; WG12232A: microprocessor, showing the characteristics and operating modes of the system; ATMEGA 16: microcontroller with ADC & DAC [7].

The studies were carried out (according to the block diagrams of Fig. 6) using traditional batteries and rectifier converters in a complex of electrochemical capacitors (EC) of the following types:

I. CAPACITOR (EC-1) type 14pp-0.5/0.015 at $U_{nom} = 14$ V with capacitance $C = 5.78$ F (3 pcs.), internal resistance $r = 0.3\Omega$;

II. CAPACITOR (EC-2) type 110pp-14/0.3 at $U_{nom} = 110$ V with capacitance $C = 5.78$ F (2 pcs.). internal resistance $r = 0.6\Omega$.

Experiments using (EC – 1) 14pp — 0.5/0.015 with the following circuit parameters:

$R_1 = 1.73\Omega$; $R_2 = 1.49\Omega$; $R_3 = 1\Omega$; $R_4 = 0.56\Omega$; $R_5 = 0.27\Omega$; $C_1 = 5F$; $U_{nom1} = 14.2V$; $C_2 = 2.5F$; $U_{nom2} = 284V$; $C_3 = 1.66F$; $U_{nom3} = 42.6V$.

Experiments using (EC-2) 14pp-0.5/0.015 with the following circuit parameters:

$U_{nom4} = 110 \text{ V}$; $R_1 = 1.21 \text{ } \Omega$; $r = 0.3 \text{ } \Omega$; $P = 10 \text{ kW}$; $C_4 = 5 \text{ F}$; $C_5 = 2.5 \text{ F}$; $U_{nom5} = 220 \text{ V}$; $R_1 = 0.60 \text{ } \Omega$; $r = 0.6 \text{ } \Omega$; $P = 20 \text{ kW}$; $C_4 = 5 \text{ F}$; $C_5 = 2.5 \text{ F}$.

For the purity of the experiments, a TDS2000071–1074–02 digital storage oscilloscope, magnetolectric ammeters and voltmeters with an accuracy class of 0.2 were used. The repetition of experiments (at different load resistances) was 6–8, the relative error was 5–7 %. The reliability of the results of experimental studies was checked with the given theoretical calculations and the regularity of determining the value of the EC capacitance for the load.

D. Overview of the interconnection project (EIJLLPST)

This project involves interconnecting the electrical grids of Egypt, Iraq, Jordan, Libya, Lebanon, Palestine, Syria, and Turkey as shown in Fig. 7. This project is symbolized by the first letter of the names of the eight countries (EIJLLPST).

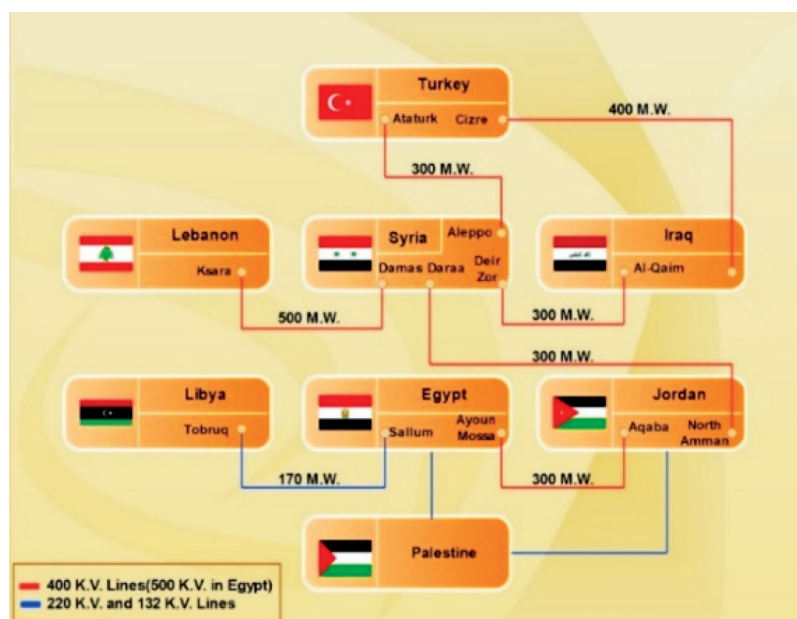


Fig. 7. The countries of the project (EIJLLPST)

It began as a five-country interconnectivity project including Egypt, Iraq, Jordan, Syria, and Turkey, expanded to six countries when Lebanon joined, and then expanded to eight countries when Libya and Palestine joined in. The Egyptian-Jordanian electrical interconnection is the first project that has been implemented to interconnect an electricity grid at 400kV in Jordan and 500kV in Egypt [8].

The implementation of this project began in 1993 and entered service in 1998 and in the same year, the electrical connection between Egypt and Libya was activated, although this interconnection was set at 220kV, not 400kV. Two other connection projects followed, one of them was to interconnect the Syrian grid to the Jordanian grid and entered service in 2001, And the other is to interconnect the Syrian grid to the Lebanese grid, which entered service in 2009 [9].

Results

A. The results experimental study of a combined power plant based on electrochemical capacitors:

$R_L(\Omega)$: Load resistance; P_C (W- kW): Power consumption; $C(F)$: Capacity of supercapacitor; $t_{ch}(ms)$: Charging time to U_{nom} ; $t_{disch}(ms)$: Discharge time to the level of $0.9 U_{nom}$; $P_A(kW/kg)$: Calculations according to the specific power at peak for the load [10, 11].

In the tables from (2) to (6) the analysis shows that the characteristic value for the developed energy storage system is the electric capacity, where the energy-intensive ionistor is able to transfer under certain discharge conditions to the electric power system.

Table 2

The results of experiments for EC at ($C_1 = 5F$; $U_{nom1} = 14.2V$)

$R_L (\Omega)$	$P_c (W)$	$C_1(F)$	$t_{ch} (ms)$	$t_{disch} (ms)$	$P_A (kW/Kg)$
$R_1 = 1.73$	88.04	5	35	390	1.8
$R_2 = 1.49$	110.76	5	35	280	1.8
$R_3 = 1$	142	5	35	200	1.7
$R_4 = 0.56$	284	5	35	100	1.5
$R_5 = 0.27$	568	5	35	28	0.9

Table 3

The results of experiments for EC at ($C_2 = 5F$; $U_{nom2} = 28.4V$)

$R_L (\Omega)$	$P_c (W)$	$C_2(F)$	$t_{ch} (ms)$	$t_{disch} (ms)$	$P_A (kW/Kg)$
$R_1 = 1.73$	88.04	2.5	16	180	0.6
$R_2 = 1.49$	110.76	2.5	16	140	0.4
$R_3 = 1$	142	2.5	16	100	0.34
$R_4 = 0.56$	284	2.5	16	60	0.09
$R_5 = 0.27$	568	2.5	16	12	0.03

Table 4

The results of experiments for EC at ($C_3 = 1.66F$; $U_{nom3} = 42.6V$)

$R_L (\Omega)$	$P_c (W)$	$C_3(F)$	$t_{ch} (ms)$	$t_{disch} (ms)$	$P_A (kW/Kg)$
$R_1 = 1.73$	88.04	1.66	10	75	0.5
$R_2 = 1.49$	110.76	1.66	10	45	0.4
$R_3 = 1$	142	1.66	10	32	0.2
$R_4 = 0.56$	284	1.66	10	22	0.09
$R_5 = 0.27$	568	1.66	10	9	0.018

Table 5

The results of experiments for EC at ($C_4 = 5F$; $C_5 = 2.5F$; $U_{nom4} = 110V$)

$R_L (\Omega)$	$P_c (kW)$	$C(F)$	$t_{ch} (ms)$	$t_{disch} (ms)$	$P_A (kW/Kg)$
$R = 1.21$	10	5	35	3.74	36
$R = 1.21$	10	2.5	20	1.87	24

Table 6

The results of experiments for EC at ($C_4 = 5F$; $C_5 = 2.5F$; $U_{nom5} = 220V$)

$R_L (\Omega)$	$P_c (kW)$	$C(F)$	$t_{ch} (ms)$	$t_{disch} (ms)$	$P_A (kW/Kg)$
$R = 0.6$	20	5	26	1.49	36
$R = 0.6$	20	2.5	20	0.7	24

B. Results of testing the impact of (ES) on the stability of the Syrian energy system:

Suppose there was a malfunction, for example, at Jader plant Syria, in the gas pipelines that feed this station. We will study the effect of this damage on the 42400 bus — JANDGT0110.5. This case was presented using the PSS/E program to show the behavior of the frequency and load angle when the power grid of eight countries was activated and supercapacitors were used at the Syrian Jandar station.

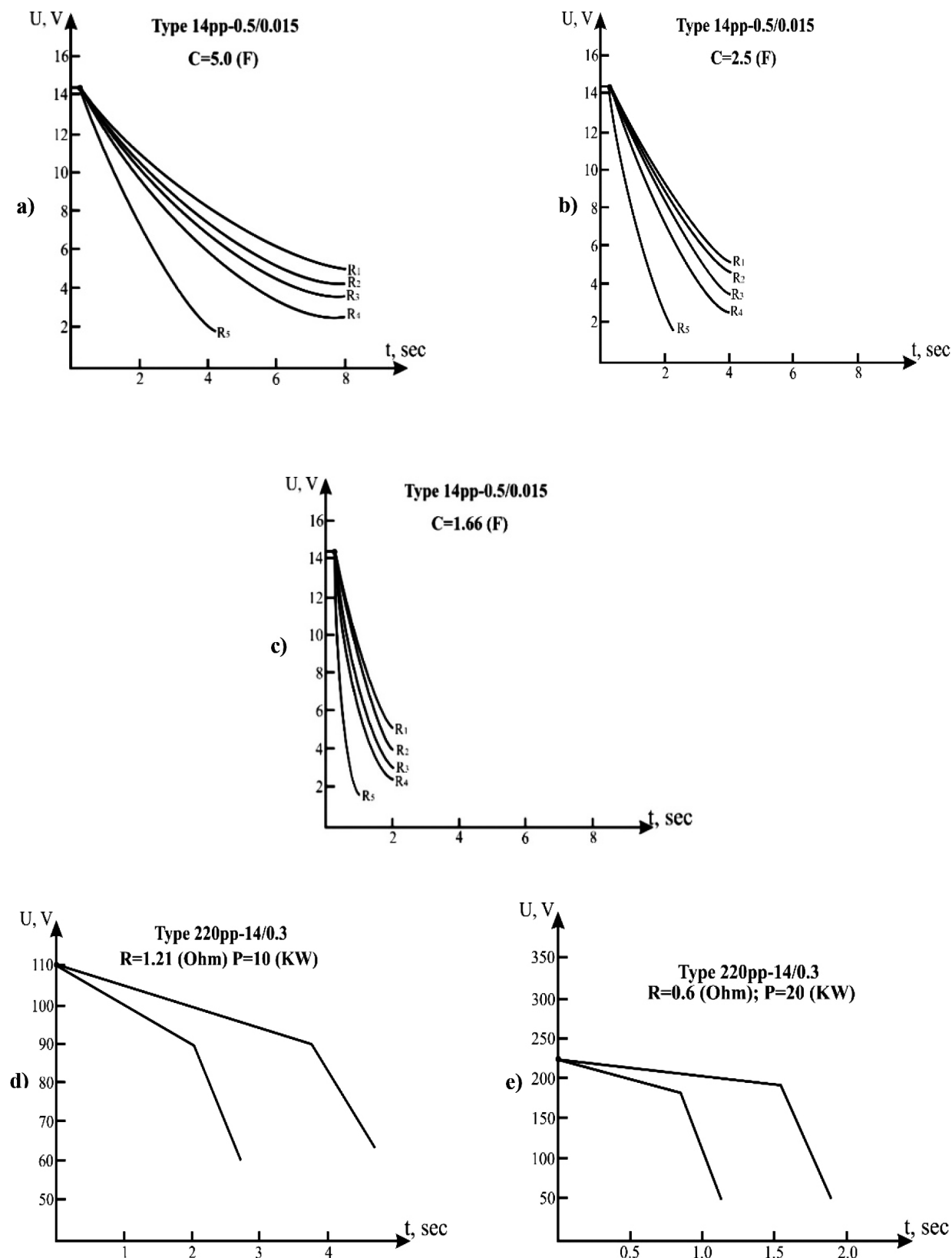
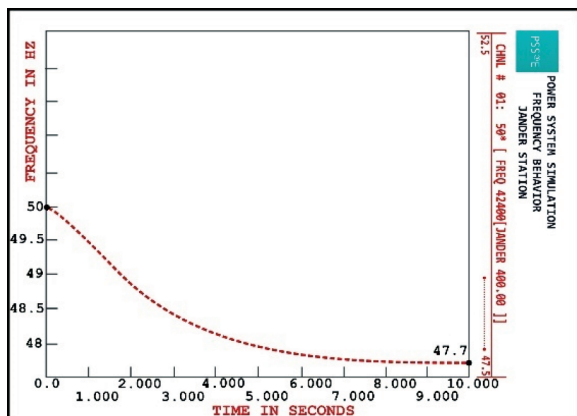
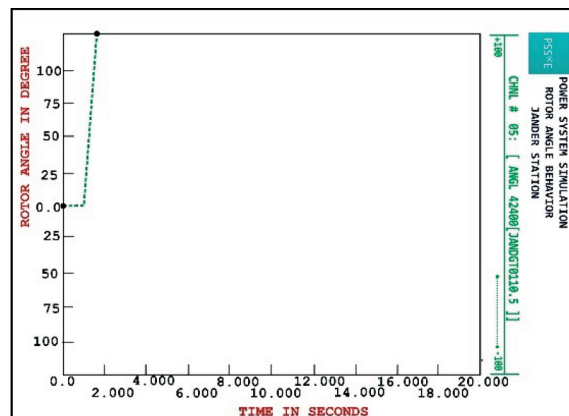


Fig. 8. Discharge characteristics of EC.

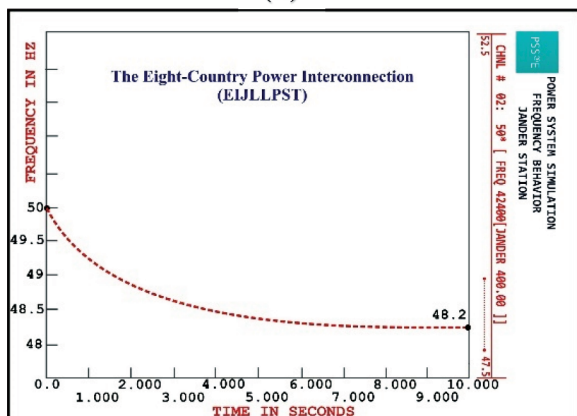
- a* — discharge characteristics of EC with capacitance $C_1 = 5$ F;
b — discharge characteristics of EC with capacitance $C_2 = 2.5$ F;
c — discharge characteristics of EC with capacitance $C_3 = 1.66$ F;
d — discharge characteristics of EC with capacitance ($C_4 = 5$ F; $C_5 = 2.5$ F; $U_{\text{NOM4}} = 110$ V);
e — discharge characteristics of EC with capacitance ($C_4 = 5$ F; $C_5 = 2.5$ F; $U_{\text{NOM5}} = 220$ V)



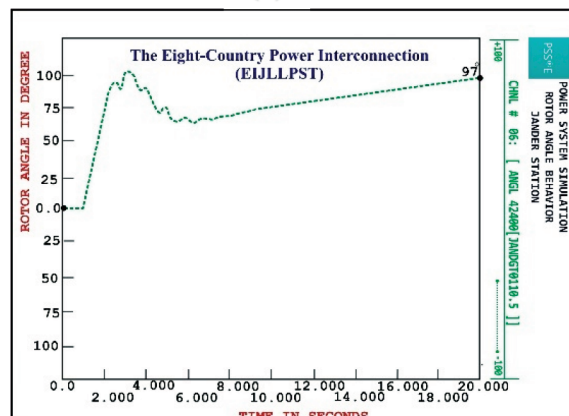
(A)



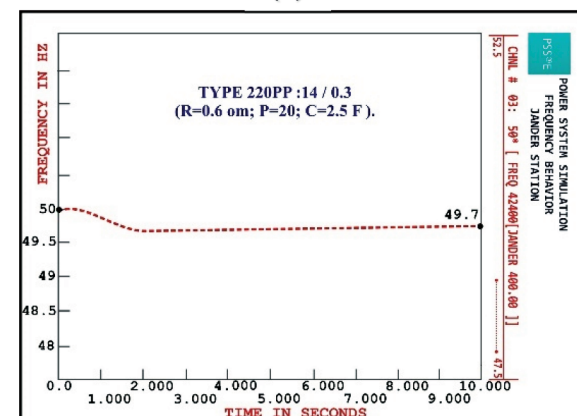
(B)



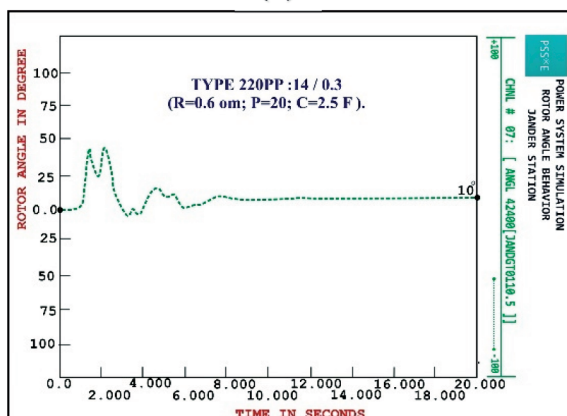
(C)



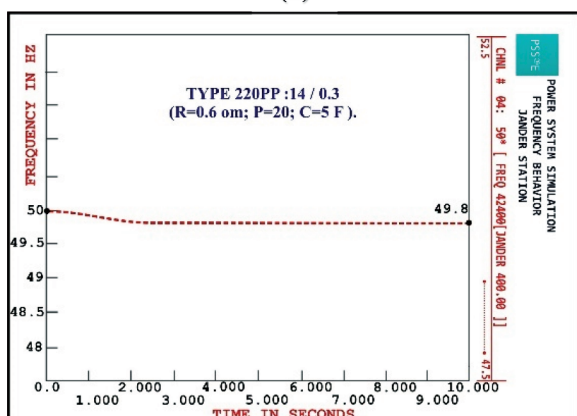
(D)



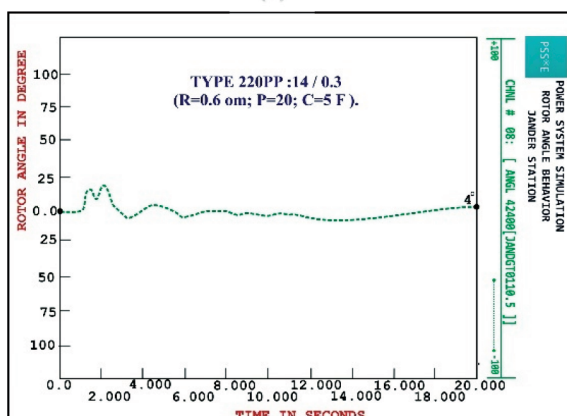
(E)



(F)



(G)



(H)

Fig. 9. Graphs of deviations of (frequency- rotor angle) of Jander plant TG-32

C. The checking the values which we got from the program PSS/E:

From equation of rotor angle and frequency of a Synchronous Generator (TG-32):

$$\left. \begin{aligned} \delta &= \delta_0 + \frac{\Delta\delta_0}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_d t} \sin(\omega_d t + \theta); \\ \omega &= \omega_0 - \frac{\omega_n \Delta\delta_0}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_d t); \\ f &= f_0 - \frac{f_n \Delta\delta_0}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_d t). \end{aligned} \right\} \quad (19)$$

Parameters of Jandar Power Plant Turbine Generator in Syria (JANDGT0110.5): Turbogenerator type (TG-32); $U_{nom}=10.5\text{kV}$; $\cos(\phi)=0.8$; $Uf_{nom}=220\text{ V}$; $f_0=50\text{ Hz}$; $H=9.9\text{ MJ/MVA}$; $D=0.138$; $\Delta\delta=10^\circ$; $T_n=5.6\text{ rad/sec}$; $T_d=5.5\text{ rad/sec}$; $f_n=0.89\text{ Hz}$; $2=1.37\text{ rad}$; $\zeta=0.194$

$$\begin{aligned} \delta &= 0,611 + 0,703e^{-1,087t} \sin(5,497t + 1,374); \\ f &= 48,2 - 0,0627e^{-1,087t} \sin(5,497t). \end{aligned}$$

Table 7

Change frequency and rotor angle for $\delta(1)=35^\circ$

t, sec	0	1	2	3	4	5	6	7	8	9	10
δ , rad	0.680	0.625	0.609	0.608	0.610	0.610	0.611	0.611	0.611	0.611	0.611
Δ , deg	38.96	35.81	34.90	34.83	34.95	34.95	35	35	35	35	35
f, Hz	48.137	48.179	48.192	48.192	48.199	48.199	48.2	48.2	48.2	48.2	48,2

$$\begin{aligned} \delta &= 0,261 + 0,703e^{-1,087t} \sin(5,497t + 1,374) \\ f &= 49,7 - 0,0627e^{-1,087t} \sin(5,497t) \end{aligned}$$

Table 8

Change frequency and rotor angle for $\delta(2)=15^\circ$

t, sec	0	1	2	3	4	5	6	7	8	9	10
δ , rad	0.323	0.274	0.256	0.258	0.260	0.261	0.262	0.262	0.262	0.262	0.262
Δ , deg	18.5	15.70	14.67	14.78	15	15	15	15	15	15	15
f, Hz	49.700	49.715	49.707	49.701	49.7	49.7	49.7	49.7	49.7	49.7	49.7

$$\begin{aligned} \delta &= 0,069 + 0,703e^{-1,087t} \sin(5,497t + 1,374); \\ f &= 49,8 - 0,0627e^{-1,087t} \sin(5,497t). \end{aligned}$$

Table 9

Change frequency and rotor angle for $\delta(3)=4^\circ$

t, sec	0	1	2	3	4	5	6	7	8	9	10
δ , rad	0.137	0.082	0.064	0.066	0.068	0.068	0.069	0.069	0.069	0.069	0.069
Δ , deg	7.90	4.70	3.86	3.82	3.90	3.94	3.95	4	4	4	4
f, Hz	49.800	49.815	49.807	49.801	49.8	49.8	49.8	49.8	49.8	49.8	49.8

Discussion

From Fig.8 a characteristic value for ES is its capacity or the amount of electricity that the capacitor is able to give under certain discharge conditions, namely current and maximum voltage.

EC for $U_{nom}=220\text{ V}$, $C=2.5\text{ F}$, $C=5\text{ F}$ are able to maintain voltage within acceptable limits on the consumer's buses with a power of 20 kW for 0.8 to 1.5 seconds. This is quite enough to ensure a reliable power supply to consumers in case of short-term power supply voltage dips.

Fig (9-A, B) shows the graph of the frequency deviation on the bus 42400 of turbogenerator (JANDGT0110.5) Jander — Syria without forcing. Frequency deviation — 4.6 % and deviation of the rotor angle — not defined.

Fig (9-C, D) shows the graph of the frequency deviation on the bus 42400 of turbogenerator (JANDGT0110.5) Jander — Syria using the Eight-Country Power Interconnection (EIJLLPST). Frequency deviation — 3.6 % and rotor angle deviations ($\delta=35^\circ$).

Fig (9-E, F) shows a graph of the frequency deviation on the bus 42400 of turbogenerator of (JANDGT0110.5) Jander — Syria with forcing in the presence of a supercapacitor-TYPE 220PP:14/0.3 ($R = 0.6 \Omega$; $P=20 \text{ kW}$; $C=2.5 \text{ F}$). Frequency deviation — 0.6 % and rotor angle deviations ($\delta=15^\circ$).

Fig (9-G, H) shows a graph of the frequency deviation on the bus 42400 of turbogenerator (JANDGT0110.5) Jander — Syria with forcing (in the presence of a supercapacitor in the excitation system -TYPE 220PP: 14/0.3 ($R = 0.6 \Omega$; $P=20 \text{ kW}$; $C=5 \text{ F}$). Frequency deviation — 0.4 % and rotor angle deviations ($\delta=4^\circ$).

Conclusion

1. Turning on ES in a complex with batteries and charging devices of power plants will increase the reliability of power supply to automatic control systems and protection of power equipment in case of short-term power outages.

2. Studies have been carried out on the use of electric energy storage devices (ES) as a means of ensuring reliable power supply to consumers in case of short-term voltage failures of the power source.

3. On the basis of static processing and analysis of data on power interconnections of the Arab countries, a significant impact on the stability of the operation of the Syrian energy system is shown.

4. An analytical solution is obtained for correcting the values of the load angle of the synchronous generator and frequency to improve the efficiency of power system stability — Syria.

5. On the basis of calculated and experimental data, specific proposals have been developed for the use of electric power storage devices based on supercapacitors to increase the stability of the operation of turbine generators in power systems.

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