A Demand Side Management Program of Vanadium Redox Energy Storage System for an Interconnected Power System

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GREECE

Abstract: - In this paper a demand side management program for an interconnected power system is proposed based on a new vanadium redox energy storage system. The program's benefits, such as the improvement of the daily load factor and the reduction of the daily load variation using a pattern recognition methodology for power system typical load profiles are analyzed proving the economic viability of the program.

Key-Words: - demand side management (DSM), energy storage system (ESS), load profiles, pattern recognition

1 Introduction

The demand for efficient energy storage systems (ESS) has been growing steadily during the last 20 years as concerns over Global Warming and urban pollution which have led to pressure from environmental groups around the world for increased use of renewable energy technologies. Energy storage can increase the value of photovoltaic and wind-generated electricity, making supply coincident with periods of peak consumer demand. ESS can also be used to support voltage and frequency, manage peak loads, improve power quality, defer upgrade investments and provide uninterruptible power for sensitive industrial and commercial applications.

These promising appliances can be super magnetic storage systems [1], super capacitors [2] and redox flow batteries [3-8]. Their techno-economic benefits are obvious in various cases, such as necessary equipment of hybrid solar wind power systems [9] or electrical cars [10], isolated islands or villages etc.

In this paper the application of dispersed vanadium redox energy storage systems is proposed for large power systems in a deregulated electricity market. After a short analysis of the specific technology, a techno-economical study is carried out comparing the proposed technology with other kind of power plants. The case of the Greek power system, taking into account the application of the new technology, has been studied using the typical daily load profiles obtained from the pattern recognition methodology presented in [11].

2 Redox Energy Storage System

The redox storage system of high energy density has been developed commercially by the following companies: Regenesys Energy Storage System [12-14], Kepco Kansai Electric Co. Inc. [15], VRB-ESS (Vanadium Redox Battery Energy Storage System) [16-18], V-Fuel Pty [3]. It is not a simple battery, but a complicate system with the capability of full, rapid charge and discharge, combined with suitable dc/ac converters for the regulation of the output reactive power. The commercial products catch up 10 MW & 100 MWh, with the capability ±10MVar, independently from the active power production. The system consists of: two electrolyte tanks, the regenerative fuel cells, the electrolyte pumps, the power source/load (case study of the interconnected Greek power system) and the respective control system. In Fig. 1 a typical storage system is presented. The redox flow cell is an electrochemical system, which allows energy to be stored in two solutions containing different redox couples with electrochemical potentials sufficiently separated from each other to provide an electromotive force to drive the oxidation-reduction reactions needed to charge and discharge the cell. Unlike conventional batteries, the redox flow cell stores energy in the solutions, so that the capacity of the system is determined by the size of the electrolyte tanks, while the system power is determined by the size of the cell stacks.

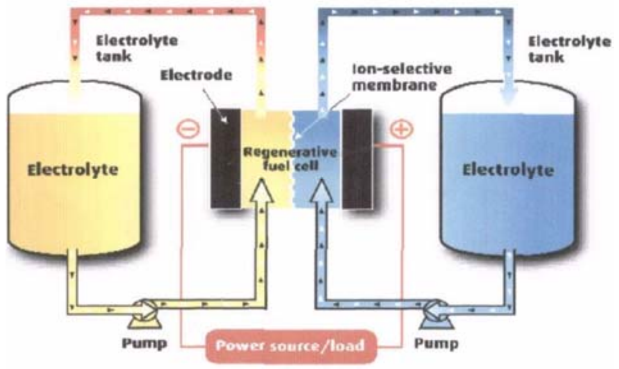

Fig. 1. Typical energy storage system by Regenesys [13]

The vanadium redox flow battery, pioneered by Skyllas-Kazakou et al [3-6, 10] has shown the greatest potential with high energy efficiency of over 80% in large installations and long cycle life. The Vanadium Redox Flow Battery employs the V^{+3}/V^{+2} and V^{+5}/V^{+4} redox couples in sulphuric acid as the negative and positive half-cell electrolytes respectively. The charge and discharge reactions occurring in the vanadium redox cell for each electrode are:

Negative $\quad V^{+3} + e^- \underset{discharge}{\overset{charge}{\rightleftarrows}} V^{+2}$ E^o=-0.26V (1)

Positive

$VO_2^{\ +} + 2H^+ + e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} VO^{+2} + H_2O$ E^o=1.00V (2)

The total standard cell potential E° is 1.26 Volts at concentrations of 1 mole per litre and at 25°C. Under actual cell conditions the open-circuit cell voltage is 1.4 Volts and 1.6 Volts at 50% and 100% state-of-charge respectively. The electrolyte for the vanadium battery is typically 2 M vanadium sulphate in 2.5 M H_2SO_4, the vanadium sulphate (initially 1 M V^{+3} + 1 M V^{+4}) being prepared by chemical reduction or electrolytic dissolution of V_2O_5 powder. The basic components of the redox cell are illustrated in Fig. 2.

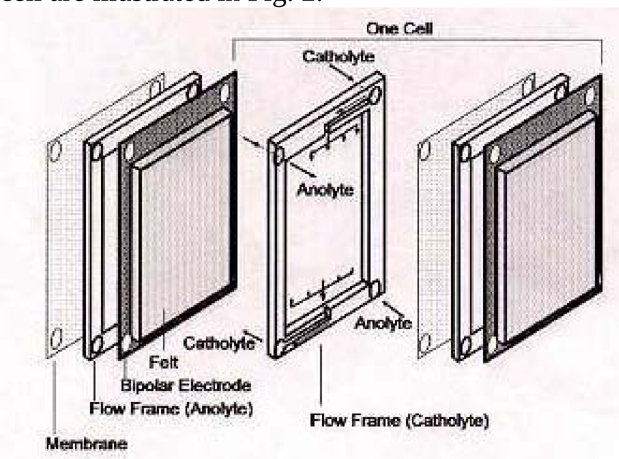

Fig. 2. Basic components of VRB cell stack [3, Fig. 3]

Most of the advantages of the vanadium battery are thus due to the use of the same element in both half-cells, which avoids problems of cross-contamination of the two half-cell electrolytes during long-term use. Consequently electrolytes life is indefinite and waste disposal issues are minimised. Other advantages are:

- low cost for large storage capacities,
- cost per kWh decreases as energy storage capacity increases, typical projected battery costs for 8 or more hours of storage being as low as 110 €/kWh,
- existing systems can be readily upgraded and additional storage capacity can be easily installed by changing the tanks and volumes of electrolyte,
- high energy efficiencies between 80% and 90% in large installations,
- capacity and state-of-charge of the system can be easily monitored by employing an open-circuit cell,
- negligible hydrogen evolution during charging,
- capable for full discharge without harm to the battery,
- all cells fed with same solutions and therefore are at the same state-of-charge,
- long cycle life,
- easy maintenance,
- it can be both electrically recharged and mechanically refueled (useful for electric car).

3 Techno-economic Study for the Application of a Vanadium Storage System in an Interconnected Power System

The vanadium redox energy storage systems are ideal for demand side management as they store electrical energy in high density, they allow high energy conversion efficiencies (over 80%) and long storage times [3]. These systems can replace the gas turbines which use natural gas or oil, as peak units for power systems. The cost is approximately determined to 530 €/kW for systems bigger than 1 MW for time duration of maximum peak load demand equal to 4 hours (330 €/kW for fuel cells and 52.5 €/kWh for electrolyte systems [3] with all necessary equipment & buildings). The duration of 4 hours has been selected based on the study of the typical daily load curves of the Greek power system [11], where it is obvious that for the most populated days the peak load lasts four hours (see also Fig. 4).

In order to compare the energy cost of different units, the equivalent annual mean cost of energy of each power plant *c* -called discounted average production cost- is defined:

$$c = \frac{D^{year}}{q} = \left[\frac{i(1+i)^n}{(1+i)^n - 1} \cdot A + f_{oc} \right] \cdot \frac{1}{h_{op}} + \left[v_{oc} + \frac{i(1+i)^n}{(1+i)^n - 1} \cdot \frac{1+p}{1+i} \cdot \frac{\left(\frac{1+p}{1+i}\right)^n - 1}{\frac{1+p}{1+i} - 1} \cdot f_c \right] \quad (3)$$

where D^{year} is the total annual capital and operational cost of the power plant, q the constant annual energy production in kWh, h_{op} the annual constant operating time in nominal active power in hours, A the total capital investment per kW (referring to all investment cost at "0" time – commercial operation of the plant), n the economic lifetime in years, i the reduction rate, p the annual increasing rate of fuel cost above the inflation, f_{oc} the constant annual operation cost per kW at "0" time, v_{oc} the variable operation cost per kWh at "0" time, f_c the fuel cost per kWh at "0" time. The equivalent annual capital and operational cost per kW and the equivalent annual mean cost per kWh - called annual power cost κ_P in €/ kW-year and energy cost κ_E in €/ kWh- are defined as:

$$\kappa_P = \frac{i(1+i)^n}{(1+i)^n - 1} \cdot A + f_{oc} \quad (4) \qquad \kappa_E = v_{oc} + f_c \quad (5)$$

The fuel cost of ESS equals to the respective one of the coal plants divided by 0.85 assuming that the efficiency of storage system is 85% [3, 17]. The equivalent annual mean cost of energy for different kind of power plants is registered in Table 1, where it is proved that the energy storage system is economically competitive with gas turbines. The rapid increase in oil prices (by extension in natural gas prices) supports this advantage of the energy storage systems (see Fig. 3). It is mentioned that nowadays (years 2007 – 2008) the percentage p is bigger than 5%, while the values of f_c (fuel cost per kWh) are rather conservative (the real values are higher now). This means that the profits using ESS against natural gas turbine are bigger in real.

It is also noted that in this preliminary economic study a large number of benefits has not been taken into consideration, such as the improvement of the reliability levels in critical loads supply (ESS operate like dispersed generators), the support of the power system's stability, the avoidance of the installation of new capacitors and inductors (ESS can product ±1 kvar / 1 kW installed capacity [3]), the load leveling, the improvement of the use factor of base power plants, etc.

4 A Proposed Demand Side Management Program of Vanadium Redox Energy Storage System

In the Greek power system Public Power Corporation has been forced to examine this alternative solution of system's support, because Greek regulatory energy authority does not allow PPC to install new power plants, until the new electricity companies possess the 30% of the total capacity according to the laws of the deregulated electricity market. From the above fiscal analysis the ESS is an economically feasible alternative solution. The case study includes the settlement of ESS of total capacity 500 MW, energy storage capability 2000 MWh with energy efficiency factor 85% (ESS can reproduce 1700 MWh) [3] divided into groups of units with a capacity from 10 MW to 50 MW in various places of Attiki region.

TABLE 1
DISCOUNTED AVERAGE COST FOR DIFFERENT KINDS OF POWER PLANTS (BASE YEAR 2000)

Kind of plant	Energy storage system	Coal plant	Gas combined plant	Natural gas turbine		
i (%)	7	7	7	7	7	7
n (years)	20	25	25	25	25	25
A (€/kW)	530	1100	700	350	350	350
v_{oc} (€/kWh)	0.0008	0.0020	0.0010	0.0010	0.0010	0.0010
f_{oc} (€/kW)	0	22.75	13	9	9	9
h_{op} (hours)	1500	7000	6500	1500	1500	1500
κ_P (€/ kW-year)	50.0283	117.1416	73.0674	39.0337	39.0337	39.0337
f_c (€/kWh)	0.0385	0.0127	0.0237	0.0382	0.0382	0.0382
p (%)	0.00	0.00	0.02	0.00	0.02	0.05
κ_E (€/kWh)	0.038	0.015	0.030	0.039	0.048	0.066
c (€/kWh)	0.071	0.031	0.041	0.065	0.074	0.092

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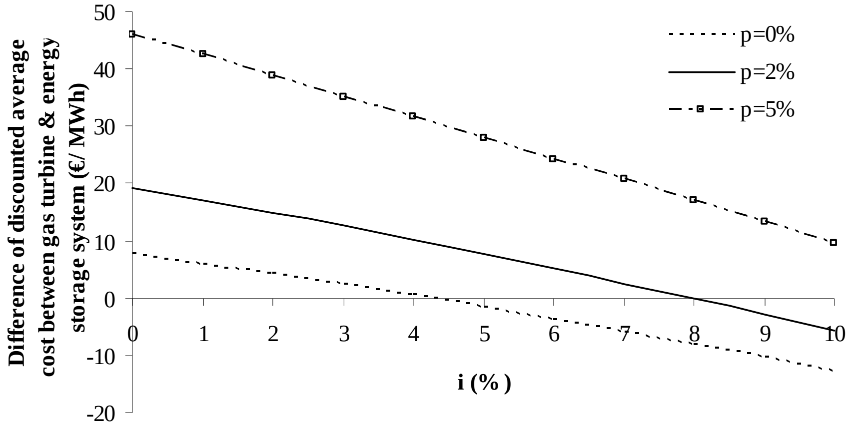

Fig. 3. Difference of discounted average cost between natural gas turbine and energy storage system in €/MWh with respect to the reduction rate i (%) for different levels of the annual increasing rate of gas cost above the inflation (p=0%, p=2%, p=5%)

Under these conditions the respective instability problems are resolved, while ESS operates like huge batteries in central medium voltage load feeders. In this way the regulatory authority and the system operator can not constrain the ESS settlement on condition that the capacity of each ESS unit is smaller than the annual minimum load demand of the feeder to which is connected.

The effects of the ESS operation to the load demand of Greek power system can be studied by using the results of the pattern recognition methodology [6], as the energy storage-reproduction cycle can last one day (not weeks or months like hydroelectric pump plants) because of the limited energy storage capabilities. We remind that the proposed pattern recognition methodology [1] is presented in Fig. 4, while the main steps are the following:

- *Data and features selection*: The active energy values are registered (in MWh) for each time period in steps of 1 hour. The daily chronological load curves are determined for the study period.
- *Data preprocessing:* The load diagrams are examined for normality, in order to modify or delete the values that are obviously wrong (*noise suppression*).
- *Main application of pattern recognition methods*: For the load diagrams, a number of clustering algorithms (k-means, fuzzy k-means and hierarchical clustering) is applied. Each algorithm is trained for the set of load diagrams and evaluated according to the ratio of within cluster sum of squares to between cluster variation. The parameters of the algorithms are optimized, if necessary. The developed methodology uses the clustering methods that provide the most satisfactory results.

The results of the respective clustering for the summer of 2000 for 10 clusters using the proposed k-means model with the optimization of the *WCBCR* indicator are presented in Fig. 5 with solid line (initial load curve).

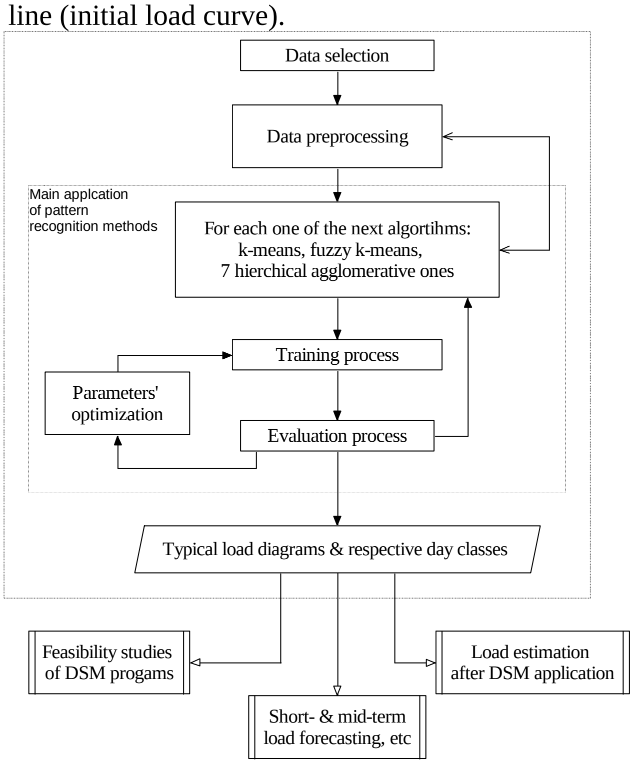

Fig. 4. Flow diagram of pattern recognition methodology for the classification of daily chronological load curves of power system [11, Fig. 1]

In Table 2 the load factor for the typical days of the summer of the year 2000 is registered before and after the application of this DSM program (where $P_{\max}^{in}$, E^{in}, f_{load}^{in} are the typical peak load demand, the total energy demand and the load factor before DSM application, $P_{\max}^{DSM}$, E^{DSM}, f_{load}^{DSM} are the respective ones after the DSM application and p_d the percentage improvement of the load factor), while in Fig. 5 the respective load curves are presented. It is obvious that as the load demand levels increases, the improvement of the load factor is lower. However the economic improvement becomes bigger, as ESS replace more expensive power plants.

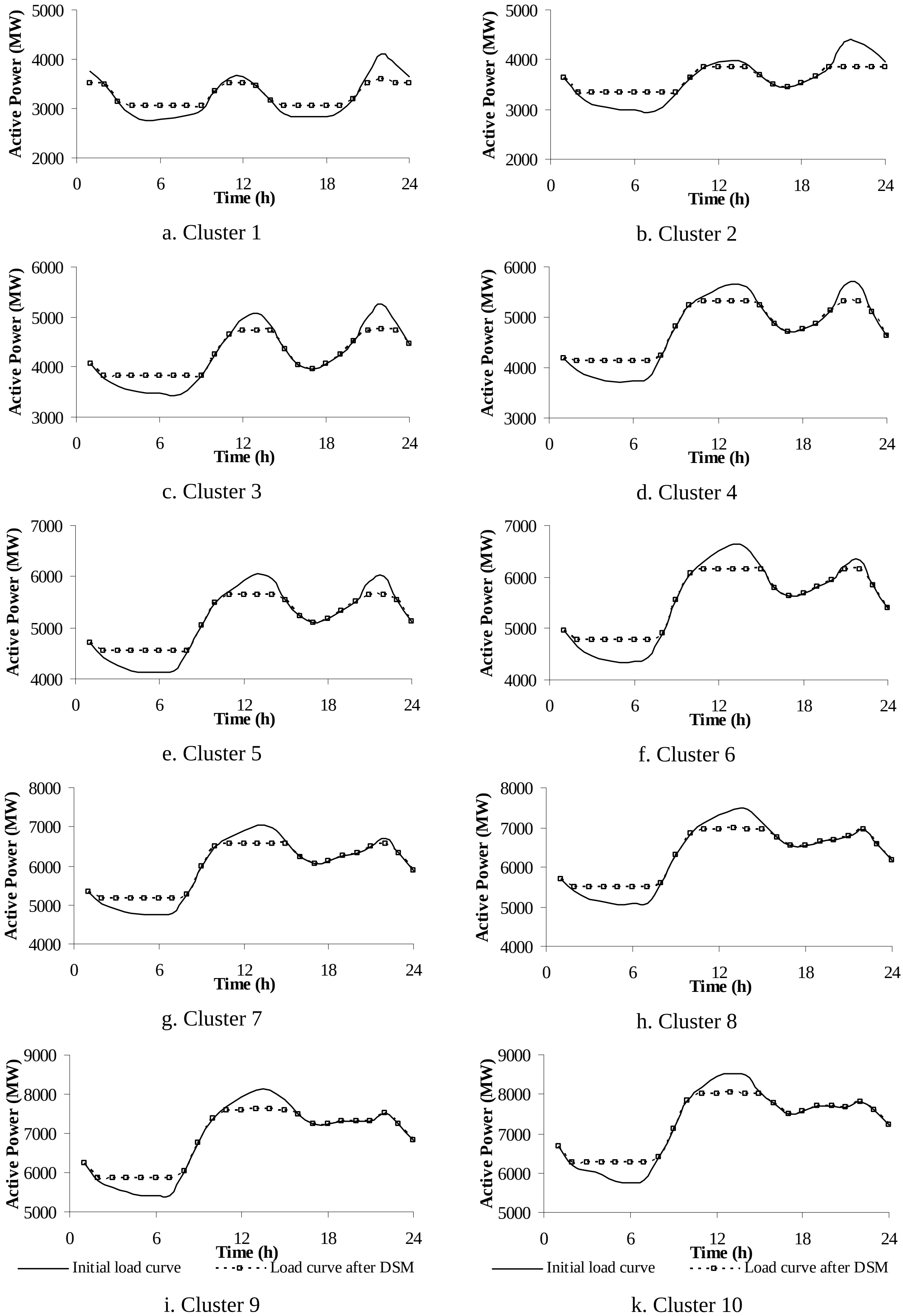

Fig. 5. Typical daily chronological load curves of the summer of the year 2000 for the Greek power system before and after DSM application (ESS 500 MW -2000 MWh) with respect to the results in [11, Fig. 6]

TABLE 2
LOAD FACTOR FOR TYPICAL DAYS OF GREEK POWER SYSTEM FOR THE SUMMER OF THE YEAR 2000 BEFORE & AFTER THE APPLICATION OF DSM PROGRAM

Typical day	1	2	3	4	5	6	7	8	9	10
$P_{\max}^{in}$	4098	4351	5264	5665	6059	6628	7030	7468	8113	8529
E^{in}	77651	86172	101285	114081	123065	132951	142762	151465	164802	173993
f_{load}^{in}	0.790	0.825	0.802	0.839	0.846	0.836	0.846	0.845	0.846	0.850
$P_{\max}^{DSM}$	3598	3858	4764	5305	5649	6149	6551	6968	7613	8029
E^{DSM}	77951	86472	101585	114381	123365	133251	143062	151765	165102	174293
f_{load}^{DSM}	0.903	0.934	0.888	0.898	0.910	0.903	0.910	0.908	0.904	0.904
p_d	14.3	13.2	10.8	7.1	7.5	8.0	7.5	7.4	6.8	6.4

In all cases of the daily typical load curves the load variation is suppressed and the final daily load demand is more flattened.

5 Conclusions - Discussion

This paper presents the techno-economic study for a demand side management program of the use of vanadium redox energy storage systems in interconnected power systems, contrary to their conventional applications in isolated power systems, such as submarines, electric cars, discontinuous villages or autonomous islands, etc. The program is economically viable and the user will have profits surely for reasonable reduction rate i (between 5% - 8%) and annual increasing rate of gas - oil cost above the inflation p (between 2% - 5%), as it is shown in Fig. 3.

The application of this demand side management program in Greek power system has proved the direct benefit obtained by the daily load demand curve flattening. Cheaper power plants will be used more during the time period of the minimum load demand (midnight hours), such as coal and combined plants, while more expensive plants will limit their operation during the time period of the maximum load demand (noon and late afternoon hours), such as gas and oil turbine plants. In this way the power system's average hourly production cost will be reduced. It is mentioned that oil and gas turbines practically have the same annual power cost per kW, but the oil energy cost is bigger than gas energy cost by 20%-25%. However, oil turbines are commonly used where there is not natural gas supply network.

There are also other advantages, such as the dispersed reactive power production near large load demand feeders which makes the power system more stable. The supply reliability of crucial loads (such as hospitals, military settlements, etc) can be increased, if we supply these loads during blackouts or network failures using ESS according to their priority level.

Under current conditions it is proposed that energy storage systems can replace oil and natural gas turbines easily.

The quantitative effects in the power system stability, operation and expansion, from this kind of demand side management programs should be investigated extensively in future.

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