Development of Techno-Economical Objective Function for Supercapacitors Energy Storage System Implemented in Distribution System

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Abstract: **The development and advancement in storage technologies and custom power devices technologies are making the application of supercapacitors energy storage system a potentially viable solution for modern power distribution system application, permitting the system to be operated in more flexible and controllable manner. The supercapacitors energy storage system considered is supposed primarily for limiting the monthly subscribed demand levels, energy cost saving, for supply of energy in case of instantaneous need and long duration back up purpose. This paper presents the development of techno-economical multi-objective function for SCESS implemented in distribution system considering the constraints and their impact on optimization of net present value.**

Keywords:
Supercapacitors Energy Storage System (SCESS), Net Present Value (NPV), Supercapacitor Capital Cost ($C_{sccapital}$), Specific Cost of Energy Capacity of supercapacitors (C_w), Specific cost of capacitance SCESS(C_{sc}), Subscribed Demand (D_{sub})

1. INTRODUCTION

The power sector throughout the world almost have gone from regulated market to the deregulated one, centralized to more localized systems that are situated nearer to the load centers. Further the strong constraint is the non-storable electrical energy should have a real time flow from generation point to the load and other constraints like occurrence of different kind of faults in distribution system, peak load, unpredictability of renewable energy sources , increased concern for environment, utilization of renewable energy technologies, flexibility of operation, lower time of project completion, construction of new transmission lines and increased customer concern for highly reliable electricity etc.

Voltage support in distribution system with loss minimization using distributed generators; such as fuel cells, solar cells, wind mills, micro gas/ hydel turbine etc has become the recent trend in electrical power distribution system. Basically the energy storage system applications can be categorized

— Grid Independent applications
— Grid dependent applications

In the grid independent applications are (a) Residential (b) Small Village (c) Large Village/Small Industry ;while in grid dependent applications (a) Power Quality (b) Voltage Regulation (c) Customer Demand Peak Reduction (d) Area control/Frequency Regulation.

Energy Storage Technology (EST) used in conjunction with DG / Grid can be divided into two groups. The First one is that stores energy as electrical energy and the second one is that which stores it in some other form (e.g. electro-chemical storage, thermal storage, hydraulic storage, pressure storage, mechanical storage, electro-magnetic storage, electro-static storage etc.), which can be converted into electrical energy when needed.

The aim of the development of techno-economical objective function is to a generalize the method for analysis of SCESS implementation technically and economically viable formulation and/or a criterion for the grid independent/ dependent applications to optimize size for the particular level in the distribution system, with and without renewable energy source. Also calculating the benefits like deferred distribution upgrade investment, reduced demand charges, reduced power quality-related financial losses, and increased revenue from renewable capacity firming, increased revenues from renewable energy time-shift [1, 2, 3, 4, 5].

2. COST CONSIDERATIONS FOR SUPERCAPACITORS ENERGY STORAGE SYSTEM

For economical analysis, the following must be considered the supercapacitors capital cost, its operating and maintenance costs and other factors on which it depends, and energy charging cost.

2.1. Supercapacitors Capital Cost

Supercapacitors capital cost is basically function of two main components. One is related to the maximum energy storage capacity, and the other one depends on capacitance

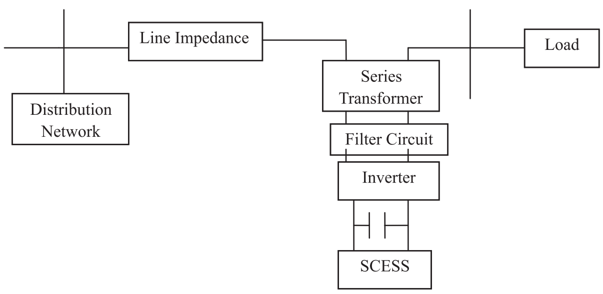

Fig. 1. Schematic diagram of a distribution network with SCESS

of the system. Therefore, the SCESS capital cost can be expressed as:

$$C_{sccapital} = C_w W_{\max} + C_{sc} C_{\max} \quad (1)$$

where:

C_w — specific cost of energy capacity in ($/kWh)
C_{sc} — specific cost of capacitance SCESS in ($/Farad)
W_{max} — maximum energy storage capacity (kWh)
C_{max} — capacitance of Supercapacitors (F)
$C_{sccapital}$ — supercapacitors capital cost ($)

Table 1. Supercapacitors Cost Components Variation Trend [6]

SI.NO.	C_{sc} ($/Farad)	C_w ($/kJ)	Year
1	0.75	281.55	1996
2	0.40	151.23	1998
3	0.01	32	2000
4	0.023	7.51	2002
5	0.010	2.85	2006
6	0.0075	2.07	2008
7	0.0063	1.68	2009
8	0.0050	1.28	2010

Table 2. SCESS Technical and Economical Data

C_w ($/kJ)	1.68
C_{sc} ($/F)	0.0063
α ($)	5%
C_{ov} ($/kWh)	5%
Efficiency	95%
Lifespan (years)	25

2.2. SCESS Operating and Maintenance cost

SCESS annual operating and maintenance cost is basically function of two main components. One is related to its annual discharged energy and other one is maintenance cost. Technical and economical characteristics considered in this study are presented in Table 2.

$$C_{scom} = \alpha + C_{vo} W_{an} \quad (2)$$

Where

C_{vo} — Variable operating cost in ($/kWh/year)
α — Fixed maintenance cost in ($)
W_{an} — annual energy discharged (kWh/year)
C_{scom} — SCESS operating and maintenance cost ($)

2.3. Energy Charging Cost

For the electric power system, the load from almost midnight to the morning is low while evening to midnight is very high and during other duration is normal in daily cycle. In addition, the use of electric power has weekly cycle. The load is lower over weekend days than week days because of lower industrial and corporate sector use. Therefore to achieve the maximum economic benefits i.e. rate of return, of SCESS, its size and the subscribed demand of TOD rates customer should select according to Table 3. Energy prices are taken from statistics done by U P Electricity Regulatory Commission for Financial Year 2008-2009(see Table 3) [4].

3. COST CONSIDERATIONS FOR PLACEMENT OF CUSTOM POWER DEVICES IN PLACE OF POWER FACTOR IMPROVING EQUIPMENTS

Integration of SCESS with the DVR/DSTATCOM can provide independent real and reactive control of lines, therefore improving system reliability, power factor thereby enhancing the over all performance of the network. Supercapacitors energy storage system with custom power devices can replace the equipment able to deliver a part of reactive power. Therefore, one method of profit estimation is to consider the total costs of such avoided equipment .The total profit due this can be expressed as:

$$C_{pfi} = \gamma + \delta Q_m + \varepsilon Q_m^2 \quad (3)$$

Where γ, δ and ε are constant parameter defined by interpolating supplier's data and Q_m is maximum reactive power produced and C_{pfi} is the power factor improving device cost within the given constraint:

$$Cos\varphi_{\min} < Cos\varphi$$

However, the cost of capacitors rated 50kVAR and above can be linearly estimated since the average cost stabilizes about $13 per kVAR [8].

Placement of custom power devices would incur the capital cost, operation and maintenance cost and some fixed charges. Therefore the expression can be written as following:

$$C_{cpd} = \gamma_1 + \delta_1 C_m + C_{cpdom} \quad (4)$$

$$P_1 = C_{cpd} - C_{pfi} \quad (5)$$

Where:

C_{cpd} — Capital cost of custom power devices in ($/kVA)
α — Fixed cost in ($)
δ_1 — constant parameter defined by interpolating supplier
C_{cpdom} — custom power devices operation and maintenance cost in ($)
C_m — custom power devices capacity cost in ($/kVA)

Table 3. Energy Purchase Costs/TOD Rates [7]

Time of Use	Peak (1700hrs-2200hrs)	Off-peak (2200hrs-0600hrs)	Normal (0600hrs-1700hrs)
Energy price($/MWh)	(+)15% of Normal Rate	(-)7.5% of Normal Rate	Normal Rate

4. COST CONSIDERATIONS DUE TO REDUCTION OF DEMAND CHARGES OF THE NETWORK

The tariff applied depends on the connection voltage: the higher it is, and lower the average network facilities used so the unit price of power/energy utilization would be lower as per UPPCL tariff. The subscribed demand is one of the basic components of the tariff, subscribed at the metering point which can be changed as per demand according to contract rules and regulation. The annual bill for utilization of the power network AB_1 can be expressed as follows for the consumer of UPPCL [8, 9]:

$$AB_1 = F + W_{tax} + (D_{sub} \times D_{ch}) + (W_{ut} \times W_{ch}) + (\zeta \times W_{ch}) \tag{6}$$

where:
F — Fix charges
W_{tax} — Electricity taxes
D_{sub} — Subscribed demand
D_{ch} — Demand charge ($/kVA/year)
W_{ut} — Energy utilized
W_{ch} — Energy charge ($/kVAh)
ζ — TOD Rates
AB_1 — annual bill for utilization of network

An unexpected demand beyond the subscribed demand by the consumer for a period results in additional bill in the form of penalty as the supply have been made available to the consumer. The expression can be written as following

$$AB_1 = p \times \sum_i \left(D_{act_i} - D_{sub_i}\right)$$

$$AB_2 = p \times \sum_i \Delta D_{chi} \tag{7}$$

Where:
$i = 1, 2, 3, 4$………..24.
p — is a constant parameter as per UPPCL it is 2 [7]
ΔD_{chi} — is the demand above the subscribed demand D_{sub}
D_{acti} — is the actual demand by the consumer
D_{subi} — is the subscribed demand by the consumer

The total annual bill for utilization ($) AB is expressed as:

$$AB = AB_1 + AB_2 \tag{8}$$

Therefore SCESS installation can be used to reduce the penalties AB_2, to be paid by the consumer due to unexpected demand above the subscribed demand (D_{sub}).

The annual benefit due to placement of SCESS can be expressed as:

$$P_2 = AB_b - AB_a \tag{9}$$

where:
AB_b — before installation of SCESS
AB_a — after installation of SCESS.

5. CONSUMER/DISTRIBUTOR'S ECONOMIC LOAD MANAGEMENT

In order to get the highest profit of energy prices differences between light-load and peak-load periods, SCESS charge/discharge operation must be scheduled so that to store lowest-price energy during light-load periods and then to deliver it during peak-load period ones for load leveling. As a result the consumer will be charged according to time-of-use/time-of-discount (TOD) rates (see Table III).The daily profit due to this scheduling can be expressed as:

$$P_3 = \sum_{i=1} W_{ch_i} \times P_i \tag{10}$$

Where W_{chi} ($/kVAh) is TOD rate and P_i SCESS production power for hour i.

6. INDEPENDENT PRODUCER POWER MANAGEMENT

The distribution network operator has the obligation to buy energy produced by an independent power producer (especially from alternative energy sources or of cogeneration energy) connected to his network. During off-peak periods and in case of independent production exceeds the distribution network load, this subsidized energy will go to the HV network. Therefore by storing in SCESS a part of this lost energy in the network can be reduced. The profit can expressed as [9]:

$$P_4 = \sum_{P_{ca_i} < 0} W_{ch_i} P_{ca_i} - \sum_{P_{cb_i} < 0} W_{ch_i} P_{cb_i} \tag{11}$$

Where:
P_{cai} — load after SCESS installation.
P_{cbi} — load before SCESS installation.

7. UPGRADES DEFERRAL OF DISTRIBUTION NETWORK

The load supplied by the distribution substation is continuously growing at an annual rate β; therefore the distribution system would require reinforcement. Traditionally upgrades necessitate the installation of an additional transformer and reconducting of distribution lines to meet the increasing demand. Peak shaving due to SCESS installation at a distribution substation will permit an upgrade (in years) of [10]:

$$\Delta N = \frac{log\left(\frac{1}{..}\lambda\right)}{log\left(1+\beta\right)} \tag{12}$$

where λ defines the reduction ratio (p.u.) of the peak load value.

Table 3. Technical and Economical Data.

C_{tran}($) of 10MVA	100,000
Inflation (i)	4.16%
Discount (d)	10%
β	8%

$$\beta = \frac{W_{con}}{8760 \times P_{sub}} \tag{13}$$

The profit due to this SCESS installation can be expressed as:

$$P_5 = C_{tran}\left(1 - \left(\frac{1+i}{1+d}\right)^{\Delta N}\right) \tag{14}$$

Where $C_{tran,}$ transformer capital cost ($), I and d are inflation and discount rates.

A net present value (NPV) is calculated by considering all the case profits, inflation and discount rates. Total net present value of all the considered profits is defined as:

$$P = \sum_{i=1}^{5} NPV\left(P_i\right) \tag{15}$$

8. TECHNO-ECONOMICAL ASSESSMENT OBJECTIVE FUNCTION FORMULATION

The goal of development of techno-economic objective function, for the supercapacitors energy storage system implemented in the distribution system, in order to maximize the net present value optimally. This is performed by economical analysis for its lifespan, considering the inflation and discount rates, taxes and other charges. The energy storage cost is a function of the storage device energy and power capacities and their specific costs depending on chosen technology. Always, the specific costs cannot be easily determined because lot of uncertainty and constraints associated so here for SCESS a generalized method has been evolved:

$$OP_{margin} = P - (C_{scom})_{npv} \tag{16}$$

$$OP_{profit} = OP_{margin} - D \tag{17}$$

$$N_{profit} = QP_{profit} - Taxes \tag{18}$$

$$C_{flow} = N_{profit} + D \tag{19}$$

$$NPV = C_{flow} - C_{sccapital} \tag{20}$$

where:

OP_{margin} — isoperating margin
OP_{profit} — is operating profit
D — is the depreciation
N_{profit} — is Net Profit
NPV — is Net Present Value
C_{flow} — is cash flow
P — is Net present value of total profit as per equation no. (14)

The tax rate and depreciation ratio are defined as :

$$T_r = Taxes \,/\, OP_{profit} \tag{21}$$

$$D_r = D \,/\, C_{sccapital} \tag{22}$$

The Net present value of SCESS to be maximized which depends of ($C_{w,}$ C_{sc}) values because $C_{sccapital}$ and D are function of ($C_{w,}$ C_{sc}).

Detail expression of NPV can now be written as:

$$NPV = C_{flow} - C_{sccapital} \tag{23}$$

$$= (OP_{profit} - T_r \times OP_{profit} + D_r \times C_{sccapital}) - C_{sccapital} \tag{24}$$

So to evaluate SCESS economical performance independently of specific costs (C_w, C_{sc}), NPV expression can be dissociated into three parts:

$$X_1 = (1 - T_r)\, OP_{margin} \tag{25}$$

$$X_2 = (1 - T_r D_r)\, W_{max} \tag{26}$$

$$X_3 = C_{max(1-T_r D_r)} \tag{27}$$

Therefore NPV can be written as:

$$NPV = X_1 - X_2 C_W - X_2 C_{sc} \tag{28}$$

This becomes multi objective optimization problem i.e. maximization of X_1 and minimization of (X_2, X_3) subject to:

— Inequality constraints:

$$P_{\max} - |P_{\mathrm{i}}| \geq 0, i = 1, 2 \ldots 24 \tag{29}$$

and:

— Equality constraints of the SCESS periodical behavior:

$$\sum_{P_i \geq 0, i=1,2\ldots 24} P_i + \eta \sum_{P_i \geq 0, i=1,2\ldots 24} P_i = 0 \tag{30}$$

9. CONCLUSION

The developed techno-economical multi-objective function can be used to find out the optimal SECSS size and the optimal subscribed demand of a TOD rates customer i.e. to find a SCESS which can save most electricity charge with least capital investment, assessment of upgrade deferral of distribution system capacity, consumer/distributor economic load management, independent producer power management and to select the subscribes demand which would minimize the total electricity charge when the SCESS in installed by proper scheduling of charging and discharging according to prevailing TOD rates and load cycle.

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