Economic Dispatch of PV-Integrated Power System with Optimally Sized Battery Energy Storage System using Particle Swarm Optimization

Lonah Nyaboke Segera

Abstract— Rapid escalation of fuel prices, depletion of fossil fuel reserves and environmental concerns have compelled power system operators to incorporate the Renewable Energy (RE) resources for example solar in the energy mix to meet the demand. Although the renewable energy resources are valuable and cost effective, they are unpredictable in nature and are dependent on weather conditions. The market for solar energy has been expanding rapidly worldwide. Solar-Photovoltaic (PV) systems generally have considerable power variations, which include voltage fluctuations and frequency variations. The intermittent power generation of a solar farm can perturb the supply and demand balance of the whole power system. Therefore, mitigating the adverse effects on the grid from an intermittent PV source has become essential for increasing the penetration level of PV systems. In the power system operations planning, the economic load dispatch of thermal generating system is one of the most important problems. Recent global inclination towards the utilization of more and more renewable energy makes this problem important than ever. Efficient and reliable planning of power system with significant penetration of these resources brings challenges due to their fluctuating and uncertain characteristics. Energy storages are emerging as a predominant sector for renewable energy applications. Recently, Battery Energy Storage System (BESS) has become a promising solution to help PV integration, due to the flexible real power control of the batteries. This research aims at conducting the economic dispatch of thermal and PV system with battery storage. The sizing methodology is optimized using Particle Swarm Optimization algorithm to minimize the cost of investment and losses incurred by the system in form of peak load shaving. The proposed methodology is tested and validated on a standard IEEE 30 bus test system.

Keywords—Battery energy storage system, Economic Dispatch, Photovoltaic, Particle swarm optimization, Renewable energy**.**

I. INTRODUCTION

The global electrical energy consumption is rising thereby increasing the demand of power generation. The use of renewable energy resources has become necessary due to depletion of fossil fuels that were widely used traditionally. Among alternatives used for the generation of electricity are a number of unconventional sources including solar and wind energy. Technological and economic progress of efficient and reliable solar-photovoltaic (PV) panels as well as the concerns about environmental issues has contributed to large penetration of solar energy in the power system [1]. With further developments in the PV technology and lower manufacturing costs, the outlook is that the PV power will possess a larger share of electric power generation in the near future. Grid-connected PV is ranked as the fastest-growing power generation technology [2]. Although the PV installation costs are still high, PV generates pollution-free and very cost-effective power that relies on a free and abundant source of energy [3]. However, the integration of these renewable sources into the power system exhibits challenges mainly due to their natural intermittency and limited predictability.

The economic dispatch (ED) is the short-term determination of the optimal output of on-line power generation units, to meet the system load, at the lowest possible cost without violation of any operational limits of generation and transmission facilities. To obtain the solution of the ED problem, we find the best distribution of the electrical power output from the available generating units. Earlier to the common use of alternate sources of energy, the ED problem looked after only the conventional thermal power generators, which use non-renewable resources as fuels. Now days it has become necessary that there be an alternate method of generation apart from the conventional thermal energy power generation, and one of the sources that has gained popularity is the Solar-PV. In recent decades, PV held a good position as there is no operating cost that causes a reduction in the total cost when integrated with the conventional system. Thus, PV applications became more practical for the generation of the power. In the case of huge penetration of varying power sources such as PV, due to the weather conditions or the day and night phenomenon thermal units requires a serious operation pattern because the outputs from PV generators are affected by the change in the radiation of solar energy. Thus, the large-scale utilization of solar energy depends on the flexible operation of the thermal units. Moreover, PV units can be paired with energy storage elements like batteries, to stack up the excess power generated during off-peak hours and give it back as generation during peak hours. For a system to have economic operation, the PV/Battery commitment and dispatch must be optimal [4]. This paper presents a proposed Economic Dispatch of a PV-integrated power system with optimally sized Battery Energy Storage System using PSO. The paper is organized as follows: in Section 2, a brief discussion on solar energy is given whereas its characteristics and integration challenges to the power system operators in regards to Economic Dispatch whereas the different types energy storage systems are presented in Section 3. Economic Dispatch is discussed in Section 4 while PSO is introduced in Section 5. The optimal BESS sizing-using PSO is given in Section 6, the problem formulation is given in Section 7. Section 8 gives the proposed method for Economic Dispatch while in Section 9 conclusions are drawn.

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II. SOLAR ENERGY

Renewable energy (RE) sources, including wind, solar and their hybrid systems, have become attractive options of providing energy globally due to low cost, no pollutant emission, energy security, easy accessibility and reduction fossil fuel consumption [1, 2, 3, 4]. The major applications of solar energy include solar thermal system, which converts solar energy to thermal energy, and photovoltaic (PV) system, which converts solar energy to electrical energy. In recent decades, PV held a good position as there is no operating cost, which causes a reduction in the total cost when integrated with the conventional system. Photovoltaic (PV) array, can be stand-alone installed for providing electricity in some remote areas or be connected to the grid for selling power generated. Because of instantaneous and unstable nature of solar energy, PV usually works with battery storage to provide continuous and stable power, by use of the PV-battery hybrid system. Solar energy is intermittent and it causes most of the undesired effects, such as voltage variations, real and reactive power fluctuations and potential effects for overcurrent and overvoltage protection. As a result, the amount of spinning reserve increases with the growth of PV penetration. Battery storage can reduce the risk of PV's intermittent power supply, and always ensure demand satisfaction [2]. Earlier to the common use of alternate sources of energy, Economic Dispatch problem looked after only the conventional thermal power generators, which use non-renewable resources as fuels. Recently it has become necessary that there is a need for alternate method of generation apart from the conventional thermal energy power generation, and one of the sources that has gained popularity is the Solar-PV. Global trend of utilizing more renewable energy gave a path for the generation of electricity keeping in mind the environmental restrictions [4].

Solar Power generation model

The output power of photovoltaic (PV) is uncertain as it is mostly affected by the environmental factors, namely the environmental random changes will inevitably lead to constantly changing of output power of PV [25, 26]. Solar power depends on meteorological conditions such as irradiance, ambient temperature that are directly related to geographical location [8, 14]. For effective utilisation of PV arrays, the characteristics should be desperately analysed. For the proposed case study, Neural fuzzy will be used to predict the solar power output considering the insolation levels in a given day. A stochastic model [16] of Solar panel is constructed based on Beta distribution function. Beta distribution is considered to be the most suitable model for statistical representation of the probability density function.

III. ENERGY STORAGE SYSTEMS

Energy storage has the potential to provide a significant portion of the flexibility needed to manage the modern grid. These include supporting the overall reliability of the electricity grid, to help defer or avoid investments in other infrastructure, to provide backup energy during power outages or other energy shortages, to allow energy infrastructure to be more resilient, to support off-grid systems and to facilitate energy access for under-served populations. In 2016, a primary driver for advances in energy storage was the demand for battery storage in Electric Vehicles (EVs).

Energy storage systems (ESS) capture energy during periods when demand or costs are low, or when electricity supply exceeds demand, and can surrender stored energy when demand or energy costs are high [2]. Recent development and advances in the ESS and power electronic technologies have made the application of energy storage technologies a viable solution for modern power application [6]. The potential applications mainly cover the following aspects. Through time shifting, the power generation can be regulated to match the loads. The ESS can also be used to balance the entire grid through ancillary services, load following and load leveling [7]. Moreover, it can meet the increasing requirement of reserves to manage the uncertainty of wind generation [8] which can increase the system operation efficiency, enhance power absorption, achieve fuel cost savings and reduce Carbon emissions. Additionally, the ESS is a potential solution to smooth out the fluctuations, and improve supply continuity and power quality [9].

Energy storage used in conjunction with renewable energy resources for example wind and solar is one of the means to increase the use of renewable energy while maintaining a high quality of service reliability. The use of storage devices can help balance the wind and solar generation output and can be used to transfer energy from low-use periods to peak-use periods, allowing the system to operate at a more constant level and reducing energy supply costs [21]. Each technology has its own performance characteristics that makes it optimally suitable for certain grid services and less so for other grid applications. This ability of a storage system to match performance to different grid requirements also allows the same storage system to provide multiple services. This gives storage systems a greater degree of operational flexibility that cannot be matched by other grid resources, such as combustion turbines or a diesel generator.

A number of different energy storage technologies exist and are under development, and their characteristics (response time, discharge time, output capacity and efficiency) and functions vary widely. As of 2016, most electric energy storage capacity relied on pumped storage, the oldest and most mature electricity storage option, as well as the largest in scale (per system). Other electricity storage technologies include batteries (electro-chemical), flywheels and compressed air (both electromechanical). Thermal energy storage, which stocks heating or cooling for later use (e.g., molten salt, ice storage, etc.) also is present in some markets and can serve both thermal applications and electricity by conversion. Only pumped storage is a highly mature technology; all others are undergoing development and transition [2].

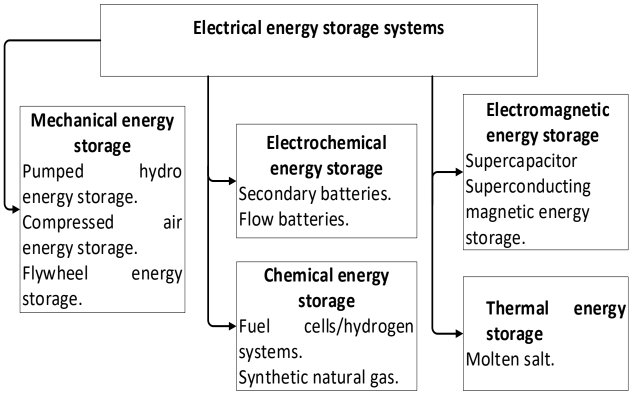

Fig. 1 Classification of electrical energy storage systems.

COMPARISON OF ENERGY STORAGE SYSTEMS

Pumped hydro storage and CAES have the lowest investment risks with respect to the cost per kilowatt-hour of electricity produced and the lowest levelised cost of delivered energy, comparable with combined cycle gas turbines. However, they are expensive to site and build, have long construction time, only suitable for large scales, have low energy density and typically result in long transmission distances. Lithium-ion batteries could potentially be a cost-effective option in the long term for short durations (less than 4 hours). Certain flow batteries such as Zn/Br and vanadium redox, and emerging options such as Fe/Cr and Zn/air, show potential for low cost in the 4 to 8 hour or longer energy duration range, however the cost of flow batteries could increase due to the associated cost of pumping the electrolyte. Fuel cells offer the highest energy density, however the capital cost is the largest among all energy storage options with one of the lowest energy conversion efficiency ranges [19].

In order to provide smooth and uninterrupted electricity supplies, it is necessary to combine different energy management strategies. Power quality management, load shifting and standby reserve are all-necessary to maximize the efficiency and reliability of the system. Each has very different desirable characteristics and the most appropriate energy storage systems will vary according to the desired role in the power management strategy. Power quality management relies on very fast response times to smooth electricity quality disturbances on a nanosecond and millisecond scale to provide uninterrupted, reliable power. The best examples for this application are flywheels, capacitors and SMES due to very fast response rates and the ability to be charged and discharged frequently whilst maintaining good operating lifetimes. Load shifting involves storing energy available in times of lower electricity demand and storing this for peak demand times. Thermal energy storage is well suited to load shifting due to low costs and good capacity, whilst batteries are most commonly used in this application. Standby reserve is an available reserve of power that can be brought online to take over from the main power-generating source if it should fail or become unavailable. Ideal energy storage systems must hold their charge for long periods and have the ability to operate for days without interruption. PHS and CAES have the largest capacity and low self-discharge, making them ideally suited to this application and the only technologies currently proven for utility standby reserve. Technologies under development that will likely be appropriate in the future include fuel cells and high temperature batteries such as Sodium Sulphur [23].

IV. ECONOMIC DISPATCH

The term "economic dispatch" refers to the practice of operating an electric system so that the lowest-cost generators are used first, followed by more expensive generators and then ramped down again when loads decrease. Economic dispatch must manage generation and demand resources efficiently over time. Electricity demand varies greatly, in daily, weekly and seasonal patterns. Because bulk electricity cannot be stored inexpensively at present, generation must be available to follow changes in load almost instantaneously, and some generation and demand reduction resources must be reserved to respond to sudden, unplanned contingencies, such as generator outages, as well as changes in customer demand and variable resource production levels [25].

Different generators have different costs, production capabilities and characteristics. A generator's production level at a point in time will be affected by how quickly it can safely move between output levels, whether it is operating in a high- or lower-fuel efficiency zone, fuel availability, and whether there is sufficient transmission capacity available to deliver its output across the grid. Grid operators adjust the output of dispatchable generators - including fossil, nuclear, geothermal and dam-impounded hydro frequently to reflect changing grid conditions. The costs associated with ramping large fossil generators up and down can be significant [26].

Increasingly, operators are looking to automatically dispatched demand-side resources and distributed storage devices to help manage small, short-term fluctuations in variable resource output. Variable generation resources like wind and solar photovoltaic are some of the fastest growing sources of capacity being integrated to the grid today. Generally, system operators accept as much electricity as possible from renewable resources, because of its low cost and only curtail reliance on these sources when forced to by limits on transmission availability or reliability considerations. While renewable generation adds variability and uncertainty to the system because the wind does not always blow, the sun does not always shine (variability), and we cannot perfectly predict when these changes will occur (uncertainty). Hence these units are not dispatchable in the traditional sense (i.e., cannot be precisely controlled by the grid operator), but their output is accepted as must-run or must-take production. [14]

V. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) also known as swarm intelligence is an evolutionary computation technique that has become a candidate for many optimization applications due to its high-performance and flexibility. Kennedy and Eberhart developed the PSO technique in 1995 based on the social behavior of flocking birds and schooling fish when searching for food. This technique simulates the behavior of individuals in a group to maximize the species survival. Compared with other evolutionary algorithms, the main advantages of PSO are its robustness in controlling parameters and its high computational efficiency [12]

Each particle represents a member of the population and it "flies" in a direction that is based on its experience and that of the whole group. Individual particles move in the search space stochastically toward the position affected by the present velocity, previous best performance, and the best previous performance of the group. The neighborhood of any particle *i* is the subset of the particles it has capability to communicate with. Each particle has three parameters associated with it; its position in the search space, its velocity and the best position it has achieved individually. In every iteration, each particle keeps track of their personal best attempt, known as pbest and keeps track of their neighboring best and global best performance known as gbest. This knowledge is used further to know a better position (optimization of solution), this method combines self-experiences and social experiences. The main concept of PSO lies in the essence that each particle in the space accelerates towards the pbest and gbest locations with a random weighted acceleration in each iteration. Each particle updates its position and velocity according to the following equations [13].

$$v_i(t) = w_{ic}\ X\ v_i(t-1) + c_1\ X\ rand_1\ X \left(P_{best\ i} - x_i(t-1) + c_2\ X\ rand_2\ X \left(g_{best\ i} - x_i(t-1)\right)\right) \quad (1)$$

$$x_i(t) = x_i(t-1) + v_i(t) \quad (2)$$

Where;

t: is the current iteration

$v_i(t),\ v_i(t-1)$ are current and previous iteration velocities respectively

$x_i(t),\ x_i(t-1)$ are current and previous particle positions respectively.

$c_1,\ c_2$ are the learning factors.

$rand_1,\ rand_2$ are randomly generated numbers in the range [0.0,1.0]

$P_{best\ i}$: is the personal best position

$g_{best\ i}$: is the global best position

The inertia constant, w_{ic} is given as;

$$w_{ic} = w_{max} - \left(\frac{w_{start} - w_{stop}}{max_i}\right) X\ i \quad (3)$$

Where;

w_{max}: is the maximum inertia weight

w_{start} and w_{stop} are the inertia weights at beginning and end of an iteration respectively

max_i: is the maximum number of iterations

i: is the current iteration number

VI. OPTIMAL SIZING OF BATTERY ENERGY STORAGE SYSTEM

PSO will be used to optimally size the BESS and the following parameters will be selected for the proposed algorithm;

- The number of particles in the swarm NP
- The number of iterations Ni
- The learning factors c_1, c_2
- The maximum inertia weight w

The flow chart of the optimal BESS size based on Particle Swarm Optimization algorithm is shown in Fig. 2 below.

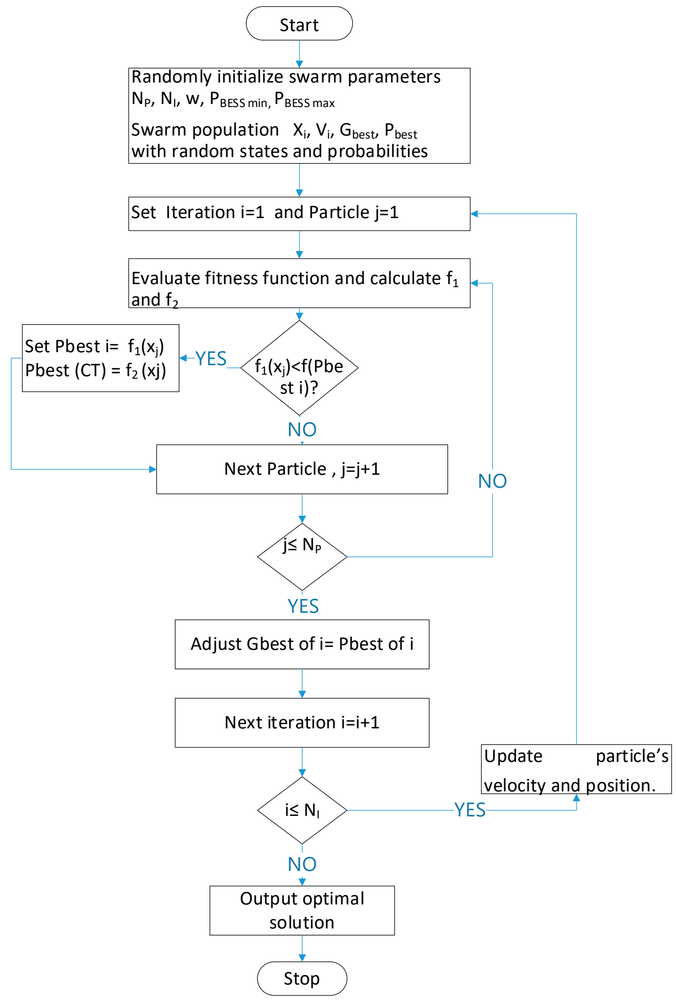

Fig.2 The overall flowchart of the proposed optimal BESS sizing based on PSO algorithm.

The BESS has to be sized optimally because an oversized BESS can be used to meet the desired features, which will lead to unnecessary high costs. On the other hand, an undersized battery may not meet the grid-connection standards. As a result, the right BESS design tool is important and beneficial for PV owners and power system planners

VII. PROBLEM FORMULATION

The PV-utility utilizes the energy generated by PV plants for minimizing the cost of operating thermal units. The PV system may be spread out over a large geographical area with a centralized location for battery. The short-term generation problem is to determine the hour for which thermal units of an electric power utility should be taken off-line or on-line. In order to produce a scheduling procedure that is practical it is essential that numerous and complex constraints are incorporated into the solution method. The mathematical scheduling problem is formulated as follows,

$$Minimize\ TC = \sum_{i=1}^{N_t} F\big(P_T(t)\big) \tag{4}$$

Where

$F\big(P_T(t)\big)$: the cost of thermal unit *i* at time t

N_t: the number of thermal generation units

Subject to

$$P_T(t) + P_u(t) = P_l(t) \quad \text{for all t} \tag{5}$$

Where

$P_T(t)$: Power output of thermal unit at time t

$P_l(t)$: the load demand at time t

$P_u(t)$: Power output of the PV plant to the utility at time t

$$C(t) = C(t-1) + \left[\frac{\Delta t\ \eta_b(t)}{V_b(t)}\Big(P_{pv}(t) - P_u(t) - P_s(t)\Big)\right] \text{ for all t} \tag{6}$$

$$P_{pv}(t) - P_b(t) - P_u(t) - P_s(t) = 0 \text{ for all t} \tag{7}$$

$$P_{pv}(t) = f\big(G_l(t), T_C(t)\big) \text{ for all t} \tag{8}$$

Where

$C(t)$: current battery state of charge at stage t (Ah)

$C(t-1)$: previous battery state of charge (Ah)

$\eta_b(t)$: battery charge efficiency at stage t

$V_b(t)$: battery voltage at stage t (V)

$P_{pv}(t)$: PV unit power output at stage t (Mw)

$P_s(t)$: spillage power from PV at stage t (Mw)

$P_b(t)$: power charge/discharge to/ from battery at stage t (Mw)

$G_l(t)$: radiation on a tilted plane at stage t (W/m^2)

$T_C(t)$: PV cell temperature [^{o}K]

Penetration limit

$$P_u(t) < P_u^{max} \text{ for all t} \tag{9}$$

Charge/discharge limit

$$|P_b(t)| < P_b^{max} \text{ for all t} \tag{10}$$

Starting state of charge

$$C(t)|_{t=0} = C_s \tag{11}$$

Ending state of charge

$$C(t)|_{t=N_t} = C_f \tag{12}$$

State of charge limit

$$C_{min} < C(t) < C_n \text{ for all t} \tag{13}$$

Fixed charge for a particular hour

$$P_b(t)|_{t\epsilon lm} = P_f \tag{14}$$

VIII. PROPOSED METHOD FOR ECONOMIC DISPATCH

The proposed system that has thermal units and photovoltaic (PV) unit with the battery system. PV generates the power proportional to the solar radiation; power from the PV unit is used to charge the battery during off-peak hours and it the battery is discharged during peak hours when demand is high. The spillage power is assumed to be zero. The output of the battery and the PV unit is DC hence the power is fed to the load via an inverter.

Initial Feasible Solution

The purpose of this algorithm is to determine the optimal battery size, which will produce optimal PV-battery generation in the initial schedule, and then the result will be used in economic dispatch problem. The objective function is to minimize the shortage of energy if there are no thermal units. The battery's State of charge (SOC) levels are used as state variables. Both starting and ending SOC, C, and C' are given along with loading periods. The constraints are available radiation and PV-battery limits.

$$Minimize\ ET = \sum_{t=1}^{N_t}\big(P_l(t) - P_u(t)\big) \tag{15}$$

Subject to;

$$C(t) = C(t-1) + \left[\frac{\Delta t\ \eta_b(t)}{V_b(t)}\Big(P_{pv}(t) - P_u(t) - P_s(t)\Big)\right] \text{ for all t} \tag{16}$$

$$P_{pv}(t) - P_b(t) - P_u(t) - P_s(t) = 0 \text{ for all t} \tag{17}$$

$$P_{pv}(t) = f\big(G_l(t), T_C(t)\big) \text{ for all t} \tag{18}$$

$$P_u(t) < P_u^{max} \text{ for all t} \tag{19}$$

$$|P_b(t)| < P_b^{max} \text{ for all t} \tag{20}$$

$$C(t)|_{t=0} = C_s \tag{21}$$

$$C(t)|_{t=N_t} = C_f \tag{22}$$

$$C_{min} < C(t) < C_n \text{ for all t} \tag{23}$$

$$P_b(t)|_{t\epsilon lm} = P_f \tag{24}$$

Economic Dispatch problem

The main objective of economic load dispatch problem is to minimise the fuel cost of the thermal generators [9]. The objective function can be formulated as;

$$F_i(P_i) = \sum_{i=1}^{N_t}(a_iP_i^2 + b_iP_i + c_i)\ \text{\$/h} \tag{25}$$

Where

$F_i(P_i)$: Fuel cost of all the generators ($/h)

a_i, b_i, c_i: Cost coefficients of ith generator.

P_i : Power generated by ith generator (Mw)

Suppose a PV-utility plant has N thermal units, the total load of thermal units at each stage is;

$$P_T(t) = P_l(t) - P_u(t) \tag{26}$$

The constraints of the optimization problem are;

Equality constraints:

The power balance of the system is given by;

$$\sum_{i=1}^{N_t} P_i(t) - P_D(t) - P_L(t) = 0 \tag{27}$$

where

P_D : Load demand (MW)

P_L: Transmission losses (MW)

Transmission losses can be represented as;

$$P_L(t) = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i(t)B_{ij}P_j(t) \tag{28}$$

where

B_{ij}: Transmission loss coefficient

Inequality constraints:

The power generation of all the generators has maximum and minimum limits

$$P_i^{min} \le P_i(t) \le P_i^{max} \tag{29}$$

Where

P_i^{min} and P_i^{max} are the minimum and maximum generation limits respectively.

Thermal unit minimum starting up/down times

$$(X_t^{on}(t-1) - T_i^{on})\big(I_i(t-1) - I_i(t)\big) \ge 0 \tag{30}$$

$$\big(X_t^{off}(t-1) - T_i^{off}\big)\big(I_i(t-1) - I_i(t)\big) \ge 0 \tag{31}$$

Ramp rate limits

$P_i(t) - P_i(t-1) \leq UR_i$ as unit i ramps up (32)

$P_i(t-1) - P_i(t) \leq DR_i$ as unit i ramps down (33)

Dynamic Economic Dispatch

The objective of the dispatch problem is to achieve the minimum production cost by properly scheduling of PV units, thermal units, battery energy storage units for the given period. The results must meet system constraints. Given the available thermal units in each stage, we solve the PV-thermal scheduling problem. The output power from a solar panel depends mainly on the irradiance. So, the power output for various irradiance values is to be estimated which requires proper functional model. The best adopted model is beta distribution function. The historical data of solar irradiance is processed and then it is utilised for modelling the beta distribution function. Using this function the output of a solar panel is estimated and then the total output obtained for the entire solar farm is calculated. This power generated by the solar farm is considered as negative demand and is incorporated at the specific point.

Then economic dispatch is carried out using this model and the results are compared. For incorporating the solar energy into the exiting generation, the power generated by PV arrays is considered as a negative load and the load equation is updated as follows:

$$P'_D = P_D - \sum_{iS=1}^{n} P_{iS} \quad (34)$$

where

P'_D : new power demand (MW)

$\sum_{iS=1}^{n} P_{iS}$: the sum of solar power generators (MW)

IX. Conclusion

The paper presents a sizing methodology to find the optimal battery energy storage capacity and power Particle Swarm Optimization algorithm to minimize the cost of investment and losses incurred by the system in form of peak load shaving. Then Economic Dispatch for a utility incorporated with PV-battery be conducted, and by incorporating battery storage, we can reduce load following requirements in the PV-utility grid. Furthermore, peaking generators can be kept off during peak hours by utilizing PV-battery. The formulation developed in this paper is very flexible and can be applied to other renewable energy sources with intermittent nature. Thus BESS makes PV power dispatchable in a similar manner to conventional sources. This show a pathway for the use of renewable energy in future for solving Economic Dispatch problem more effectively.

Appendix

Power generation from PV array

The expected output of PV is given by;

$$P(S) = P_o(S) * f_b(S) \quad (35)$$

The total output of the PV array corresponding to specific time segment is given by;

$$TP = \int_0^1 P_o(S) * f_b(S) dS \quad (36)$$

where power generation of panel at solar irradiance s is given by

$$P_o(S) = N * FF * V_y * I_y \quad (37)$$

where

N: the total number of PV modules.

The voltage - current characteristics of a PV module for a given radiation level and ambient temperature are determined using the following relations

$$FF = \frac{V_{MPPT} * I_{MPPT}}{V_{OC} * I_{SC}} \quad (38)$$

$$V_y = V_{OC} - K_v * T_{cy} \quad (39)$$

$$I_y = S\left[I_{SC} + K_i\left(T_{cy} - 25\right)\right] \quad (40)$$

$$T_{cy} = T_A + S\left(\frac{N_{OT} - 20}{0.8}\right) \quad (41)$$

where

FF: the fill factor,

V_{MPPT}: the voltage maximum power point

I_{MPPT}: the current maximum power point,

V_{OC}: the open circuit voltage

I_{SC}: the short circuit current of PV module

K_v: the voltage temperature coefficient and

K_i: the current temperature coefficient,

T_A : the ambient temperature

T_{cy}: PV cell temperature

N_{OT} : normal operating temperature

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