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INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

POWER FLOW OPTIMIZATION IN MICRO GRIDS WITH ENERGY STORAGE

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ABSTRACT

Storage of energy may be improved by power management that include renewable energy sources. The smooth and much energy balance can be achieved by using the storage devices which matches the generated to the consumption. Optimal control of the control of the micro grid's energy storage devices is addressed in this project. To optimize the overall power utilization at the micro grids point of common coupling (PCC) the storage devices are controlled to balance the power generation of renewable sources. Limits imposed by the storage device such as internal losses and limited capacity are emphasized in the recent works. The solution of optimal power flow considers the total system which is proposed in this project. The storage device limits, current limits, voltage limits and power limits. The proposed solver gets the globally optimal solution even though the power network is arbitrarily complex.

KEYWORDS: Energy storage(ES), and Distributed generation (DG), Optimal Power Flow(OPF), smart grid.

INTRODUCTION

Micro grids are integrated into distribution generation to the electricity grid . So microgrids have gaining importance [1],[2]. Confined clusters of loads small generators and storage device are connected at a point called point of common coupling (PCC) and connected to the public distribution grid through this PCC. The following figure 1 indicates the typical micro grid network. Variety of technologies used in micro grids : renewable energy sources (RES), such as wind generators and photovoltaic (PV) beside traditional high inertia synchronous generator, fuel cells and batteries [3]. The losses are reduced and reliability is increased by generating energy near the loads through small scale generators. The micro grid network provides increased management of energy. The power flow is optimized within the network by generators and possibly loads may be controlled through local energy management system (EMS). The goal of energy management depends on the mode of operation. Grid connected or Islanded.

In grid connected mode, distinctive goal is to decrease price of energy import at the point of common coupling(PCC), to increase the power factor at the Point of common coupling and to optimize profile of the voltage within micro grid [4],[5]. This work addresses the grid connected networks. In islanded mode, the main objective is power management to stabilize the system, in terms of the frequency and the voltage.

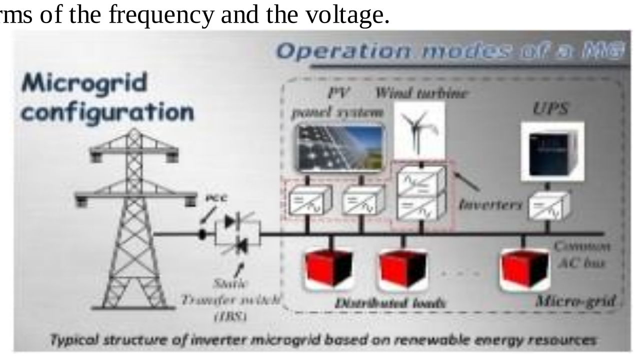


Fig.1. Typical Microgrid

In the micro grids the energy management is generally thought of as a three level stratified control system [6]. The initial control level, often called "autonomous " or "primary" control consists of a several number of local, autonomous controllers. The power electronics converters are controlled by every controller and is responsible to interface generators, loads and storage devices with the micro grid [7]. These controllers are the fastest, as they function in millisecond range and in islanded mode [2] , a droop control employed. A secondary level incorporates a low band width communication to fix the amplitude and frequency of units of the microgrid to restore their nominal values. Lastly, the third control level, related to the control of the active and reactive power flow in the system . This level of control is belongs to the energy management system (EMS) [2] and to optimization of the resources of the micro grids and is the essential subject of this work.

The third control level uses optimal power flow solver (OPF) since it coordinates the power flow within micro grid. This type of solvers are extensively used by many people. Surveys are found at [8] and [9]. However for microgrid analysis classical power flow solutions are not used, particularly due lacking in the representation of distributed energy sources, pricing methods and storage devices. The micro grid's unique aspects optimal power flow are shown latently in several studies. These studies can be classified by focus. A first group studies the optimal power sharing of distributed generators and allocation, very frequently solar or wind [10],[11]. A next group emphasizes economic revenue. The main objective of this is to minimize the overall price of energy or to maximize the profit from the generation of energy [6],[12].

The Optimal dispatch of energy storage devices is examined by the third group [13]-[16]. When the energy import is cheap or when the renewable power is available energy may be stored. This stored energy may be used later when the demand is large or when renewable power is not available. The main goal here is to optimize efficiency, price, and stability, considering the constraints required by the storage devices, such as internal losses and limited capacity. For example [13],[14], the storage device functions as intermediary generation of the power. Globalgeneration of power is optimized to be as constant as feasible, decreasing fuel costs, while taking into the limited storage capacity. The study in the [15] utilize strategy to time shift the generation of renewable, matching generation to utilization. The study in [16] addresses a wind farm, which is compensated by battery energy storage. The objective is to control the storage devices for increasing the predictability of the power generation.

The studies mentioned above all assume trivial network topologies. None of them examine storage devices incorporated in a usual power network. Optimal solution has not been shown to a generally meshed network with storage devices. The reason for this very great numerical complexity of the problem, which incorporates both the time domain and network domain, associated with storage. Traditional gradient based solvers like Newton-Raphson, althoughhighly useful in the network domain are insufficient in the time domain and could not be applied to the combined network-storage problems (see the details in section III).

To overcome this problem this work introduces a new solution method to this problem; an optimal power flow solver (OPF) solver which integrates storage devices. The proposed method evaluates the always optimal power flow, in both the time and the network domains. It take into account both the limitations of the network and storage device regarding currents, voltages and powers. The method associates a power flow solver with a dynamic programming recursive search, obtaining numerically powerful solution.

TOPOLOGYOF NETWORK AND POWER FLOW EQUATIONS

This work uses the familiar nomenclature of a power flow analysis [8].The buses are indicated by running basis i, where i = 1...N. N is the total number of buses. Each bus is i characterized by four independent signals:

$P_i(t)$ – the injected, active power from the bus into the grid (which is positive for generators and negative for loads)

$Q_i(t)$ – the reactive power, injected into the grid;

$V_i(t)$ – the magnitude of the bus voltage ;

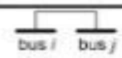
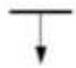
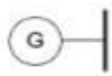
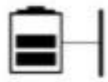
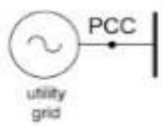
$\delta_i(t)$ – the phase angle of the voltage V_i .

In Table 1 the basic units of micro grid are indicated. It defines single phase units,unbalanced three phase units, or balanced three phase units, with per phase representation ("x" indicate the phase, A, B, or C moreovereliminated for balanced three – phase). The point of common coupling(PCC) stands for the

ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

"slack" bus. It is always indicated as bus 1(i=1) and is indicated as a V-δ bus, with $V_1(t) = V_{in}(t)$ as an uncontrollable voltage signal.

Table I Units of The Micro Grid

Unit	Symbol	Constraints	model refs
power line		**Constraints:** $I_{i,j,x}(t) < I_{i,j,max}$	
load		**Constraints:** $P_{i,x}(t) = -P_{L,ix}(t)$ (fixed) $Q_{i,x}(t) = -Q_{L,ix}(t)$ (fixed) $V_{ix,min} \le V_{ix}(t) \le V_{ix,max}$ **Free variables:** $V_{ix}(t)$, $\delta_{ix}(t)$	
Renewable generator		**Constraints:** $P_{ix}(t) = +P_{g,ix}(t)$ (fixed) $Q_{ix}(t) = +Q_{g,ix}(t)$ (fixed) $V_{ix,min} \le V_i(t) \le V_{ix,max}$ **Free variables:** $V_{ix}(t)$, $\delta_{ix}(t)$	
storage device		$E_{ix}(t)$ = stored energy or state of charge (SOC). **Typical constraints:** $V_{ix}(t) = V_{S,i}$ (fixed) $0 \le E_i(t) \le E_{i,max}$ $-P_{i,rated} \le P_i(t) \le +P_{i,rated}$ **State equation (one-phase):** $\frac{d}{dt} E_i = f_i(P_i, E_i)$ **Free variables:** $P_i(t)$, $Q_i(t)$, $\delta_i(t)$, $E_i(t)$	[13]-[15]
point of common coupling (PCC)		The PCC is always indexed as bus 1, i=1. **Constraints:** $\delta_{1,x}(t) = 0$ $V_{1,x}(t) = V_{in,x}$ (fixed) $Q_{1x,min} \le Q_{1,x}(t) \le Q_{1x,max}$ $P_{1x,min} \le P_{1,x}(t) \le P_{1x,max}$ **Free variables:** $P_1(t)$, $Q_1(t)$	[8], [10]

Renewable generators and Loads are uncontrollable and are therefore shown by fixed power signals (power versus time. The power flow equations for a balanced three phase system are given in

$$P_i = V_i \cdot \sum_{j=1}^{N} Y_{ij} \cdot V_j \cdot \cos\left(\delta_i - \delta_j - \theta_{ij}\right)$$

$$Q_i = V_i \cdot \sum_{j=1}^{N} Y_{ij} \cdot V_j \cdot \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (1)$$

$$I_{ij} = \left| V \cdot e^{i\delta_i} - V_j \cdot e^{i\delta_j} \right|$$

These equations may be found in manyacademic textbooks, such as [8]. In the (1), Y_{ij} and θ_{ij} are admittance's magnitude and phase respectively, Y_{ii} are the self admittances, $Y_{ij}(i \neq j)$ are the magnitude of cross admittances, and $I_{ij}$are the magnitude of the line currents.

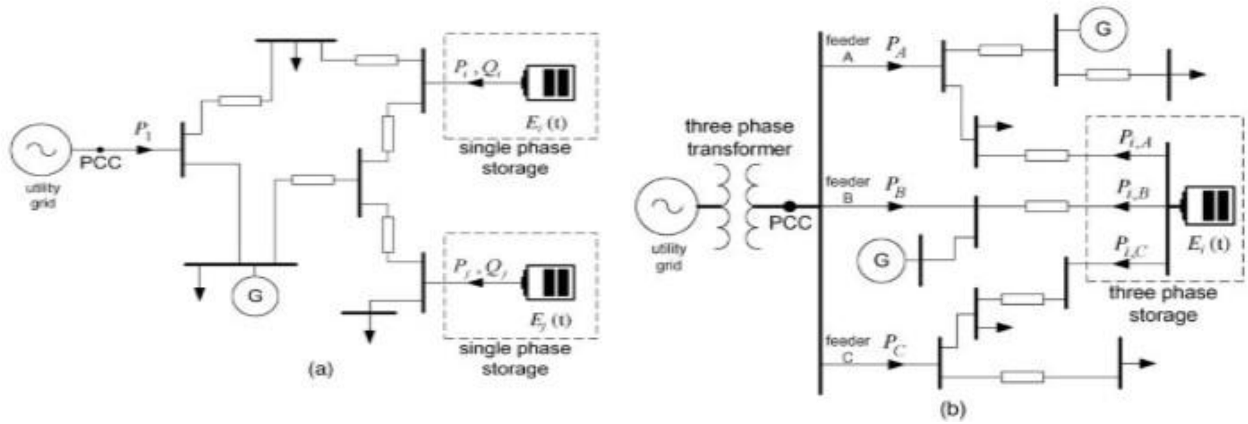


Fig.2. Depiction of single phase or three phase devices and storage devices. (a) Two storage devices in single phase system. (b) Three phase storage devices in the three phase system.

The system could also be an unbalanced three –phase system. For this case the power flow equations are too complex to be defined in the present scope, and are fully described in [17].For simplified unbalanced system, in which impedances of the neutral line are taken as zero, and leakage currents are neglected.

The power flow equations are given by

$$P_{i,x} = V_{i,x} \cdot \sum_{j=1}^{N} Y_{ij,x} \cdot V_{j,x} \cdot \cos\left(\delta_{i,x} - \delta_{j,x} - \theta_{ij,x}\right)$$

$$Q_{i,x} = V_{i,x} \cdot \sum_{j=1}^{N} Y_{ij,x} \cdot V_{j,x} \cdot \sin\left(\delta_{i,x} - \delta_{j,x} - \theta_{ij,x}\right) \quad (2)$$

$$I_{ij,x} = \left| V_{i,x} \cdot e^{i\delta_{i,x}} - V_{j,x} \cdot e^{i\delta_{j,x}} \right|$$

Where the sub-index "x"indicates the phase A, B or C. In section IV describes how these various system representations are integrated and the suggested time-domain solver.

The storage devices are modelled by an inner state variable –$E_i(t)$ the storage energy. They are specified by f(.) a general state equation, given in below.

Single – phase storage device:

$$\frac{d}{dt} E_i = f_i\left(P_i, E_i\right) \quad (3)$$

Storage device for three phase :

$$\frac{d}{dt} E_i = f_i\left(P_{i,A}, P_{i,B}, P_{i,c}, E_i\right) \quad (4)$$

Where $P_{i,A}, P_{i,B}, P_{i,c}$ represents the three phase powers at the PCC [see fig. 2(b)].

The mission is to minimise the overall priceof imported energy from the public grid, found by incoming power at the PCC. The objective for a single phase system is

$$\int_0^T P_i(t) \cdot C(t) dt \rightarrow \min \quad (5)$$

Where C(t) indicates the price signal ($/MW), which is usually a time dependent function. The objective function for an unbalanced three phase system is

$$\int_0^T (P_A(t)+P_B(t)+P_C(t))\cdot C(t)dt \rightarrow \min \quad (6)$$

Objective for a three phase system in an unbalanced state may be balancing the power amidst the phases:

$$\int_0^T \left((P_A(t)-P_B(t))^2+(P_B(t)-P_C(t))^2\right)dt \rightarrow \min \quad (7)$$

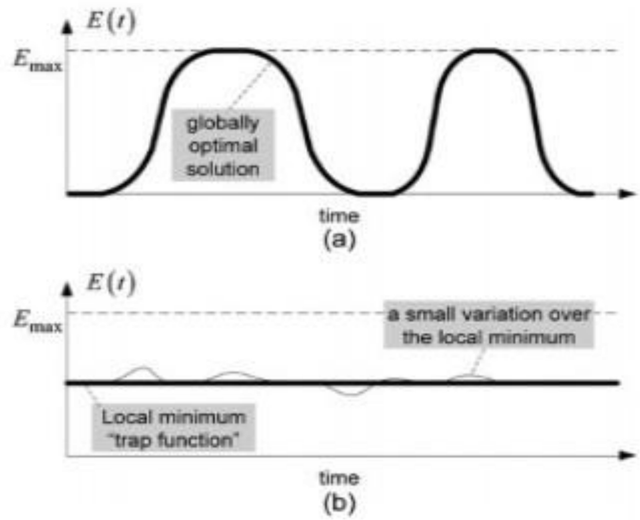


Fig.3. In time domain global and local solutions (a) Global solution (b) Local solution (bold) with a small variation(thin). Due to charge in discharge losses, the variation is energetically worse than the local solution.

GRADIENT BASED SOLVERS IN THE TIME DOMAIN

An optimal solution demands the computation of active and reactive powers (P,Q), currents (I), voltages (V), phase angles (δ), and stored energy (E). All of these quantities are dependent on time. While the gradient based solvers (like Newton – Raphson) have proven to solve networks efficiently, they insufficient for storage problems. This claim is explained below.

The required solution is a function of stored energy E(t) versus time (t). To obtain a solution, the solver must find the energy E(t) at every point, hence each time point is a free variable. Intuitively, several many time – energy functions are local minima. For example, consider the straight horizontal line in fig.3(b).Presume a slight perturbation on this possible solution. Charging and discharging are wasteful due to inefficiencies of the storage device, therefore with reference to the objective, the perturbation is fewer efficient and is poor than the straight line solution. Hence the straight line is "surrounded" by solutions which are poor and are, in fact, a local minimum.

Although there is no mathematical prooffor this explanation, by no means, it focuses the numerical complexities of gradient based solvers, which is adapted to solve the problems in the time domain. If a gradient – basedsolvers obtain a local solution,like straight line in fig. 3(b), it will infer that it is optimal.Anyhow, this is local solution does not match the global one and does not possessrequired properties. Thiscannot be utilized in a real power system since the local solution is unsuitable.

DYNAMIC PROGRAMMING APPROACH

Unlike the gradient based methods, dynamic programming algorithms (see [18]) scans all feasible solutions to find the global optimum. Optimal solution is designed recursively in the time domainby mixing dynamic allocation, with a conventional power flow solver on the network domain since the direct scan of total solution is numerically impossible,

ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

SINGLE STORAGE DEVICE – ONE DIMENSIONAL SOLUTION

The stored energy function $E_i(t)$ controlsthe power flow of the network with a single one phase storage device. By using the storage state (3) the power output of the storage device is calculated for a given energy function.The accessory may be replaced by abetting P-V unit, with accepted power and voltage valuesby presuming that magnitude the voltage of the device is denoted by $V_i(t) = V_{s,i}$. Recall that the renewable generators and loads are defined,so given power output of the storage, power flow over the total network could be calculated. This can be easily achieved utilizing standard power flow algorithms, such as Gauss-Seidal, or Newton – Raphson. Therefore the problem is one dimensional, havingone controllable state variable $E_i(t)$.

The defy is to find the energy function $E_i(t) = E(t)$ which is to diminish the objective equation (5) and satisfy all constraints listed in Table I. For this, a value function is defined V(.) is defined as

$$V(t,E) = \int_t^T P(\tau)\cdot C(\tau)\cdot d\tau - (8)$$ with an initial condition E(t) = E.

To minimize the overall cost over the entire period, starting with an empty storage E= 0 is achieved by the objective equation (5) is equivalent to minimizing V(0,0). The calculations are numeric over a discrete grid. dE marks the energy step and dt marks the time step. The optimal solution is computed by using the Bellman equation

$$V(t,E) = \min_{E(t+dt)}\{\Delta V(E, E(t+dt)) + V(t+dt, E(t+dt))\} \quad (9)$$

The value equation $V(t,E)$ is calculated using backward recursion. At the final time $t = T$,the process begins where the value function is known: $V(T,E) = 0$. The value function could be calculatedat $T - dt$, by using (9), revealing $V(T,E) = 0$. The process continues until reaching $t = 0$. The fig. 4(a) shows a backward recursion step.

For every two arbitrary points {t,E(t)} and {t+dt, E(t+dt)} the differential cost ΔV is defined. It stands for the cost of transition between two points. The following steps are followed while computing ΔV.

Step 1) The first derivative of energy is assessed by

$$\frac{d}{dt}E \approx \frac{E(t+dt) - E(t)}{dt} \quad (10)$$

Step 2) $P_i(t)$, The power output of the storage device is evaluate. Using the known values of E(t) for solving the storage state (3),revealing $P_i(t)$.

Step 3) An auxiliary $P - V$ source replaces the storage device, with $P = P_i(t), V = V_{s,i}$. A network power flow analysis is calculated by using Newton Raphson, Gauseidal, or any other method.

Step 4) The differential ΔV is assigned a value according to the power at the PCC, $P_1(t)$, if the power flow solution adhere to constraints. Otherwise, it is assigned a value of infinity

$$\Delta V = \begin{cases} P_t(t)\cdot C(t)\cdot dt, constra\operatorname{int} s \\ \infty, otherwise \end{cases} \quad (11)$$

The optimal energy $E^*(t)$ may be evaluated by computing $V(t,E)$ overall times and energies. To recover the optimal solution known values of $V(t,E)$ are substituted in the Bellman's equation.

$$E^*(t) = \arg\min_{E(t)}\{\Delta V(E^*(t-dt), E(t)) + V(t, E(t))\} \quad (12)$$

Energy $E^*(t)$ at time t is computed in relation toa earlier energy value $E^*(t-dt)$.At t=0 the computation process starts , in which the optimal energy known at equals the starting condition, usually $E^*(0) = 0$. Using [12] the optimal energy at next time step $E^{*ast}(dt)$ is computed. Until the entire optimal path has been found, up to the final time t=T the process is continued.

MULTIPLE STORAGE DEVICES

Adimension to the solution space is contributed byeach storage device.Hence, a network is considered as two dimensional problem when it has two storage devices with two free variables: $E_i(t)$ and $E_j(t)$. Instead of one energy function the power flow is governed by two energy functions. Fig. 4(b) shows the 2 –D computation.

Multidimensional solutions are must equivalent to single dimension solutions.The value function, $V(\cdot)$ is main difference , whichis now multi dimensional. For example consider a single phase network having two storage devices. The value function for this is defined as given below:

$$V(t, E_i, E_j) = \int_t^T P_1(\tau) \cdot C(\tau) \cdot d\tau \qquad (13)$$

Initial condition

$$E_i(t) = E_i, E_j(t) = E_j$$

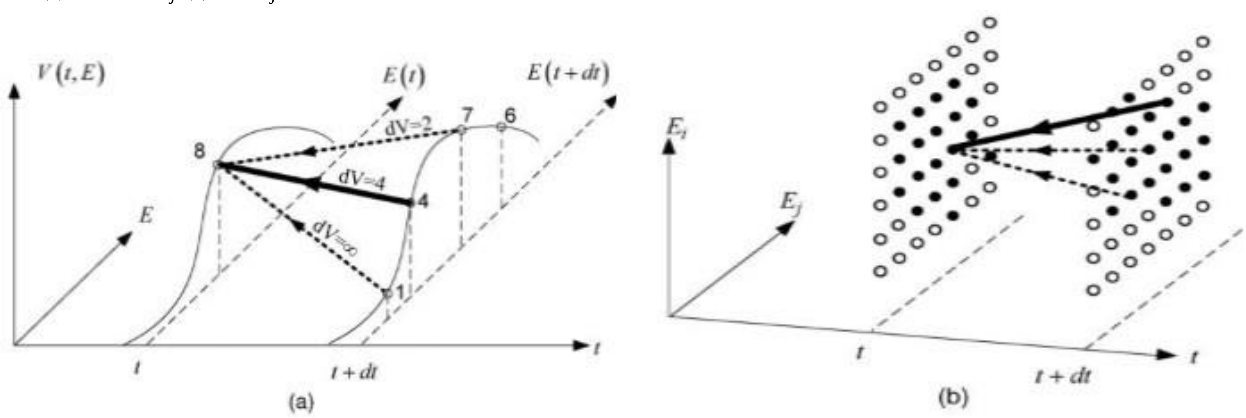


Fig.4. Backward recursion process by adopting Bellman equation.At each point the value function equals to the minimal over all of the differential paths from t to $t+dt$. Dashed lines indicates possible paths and the optimal path is indicated in bold. (a) One storage device, having one state variable $E(t)$. (b) multidimensional two storage device with two variables - $E_i(t)$, $E_j(t)$ Black dots marks the feasible solution. White dots marks the numerical grid.

This is a function of both $E_i(t)$ and $E_j(t)$. Now the Bellman equation involves minimization over both energy variables.

$$V(t, E_i, E_j) = \min_{E_i(t+dt), E_j(t+dt)} \begin{Bmatrix} \Delta V(E_i, E_i(t+dt), E_j, E_j(t+dt)) \\ + V(t+dt, E_i(t+dt), E_j(t+dt)) \end{Bmatrix} \qquad (14)$$

The differential cost ΔV is calculated for two dimensional (2-D) points $\{t, E_i(t), E_j(t)\}$ and $\{t+dt, E_i(t+dt), E_j(t+dt)\}$ [see the fig.4(b)].

The calculation includes evaluation of two derivatives as given below.

$$\frac{d}{dt}E_i \approx \frac{E_i(t+dt) - E_i(t)}{dt}$$
$$\frac{d}{dt}E_j \approx \frac{E_j(t+dt) - E_j(t)}{dt} \qquad (15)$$

These are used for calculating the output power of both storage devices. The network power flow is computed normally using this data, by using Newton Raphson or Gauss-Seidel. The differential ΔV is given a value according to the power at PCC or designated a value of infinity in case the solution is not feasible.

Storage devices in three phase could be one dimensional(1-D) or three dimensional (3-D). A balanced three storage phase device, having equal powers $P_{i,A} = P_{i,B} = P_{i,C}$ is 1-D. In accordance with the storage state equation (4), the stored energy $E(t)$ gives the three phase powers. At each time point athree-phase power flow analysis is calculated by knowing the storage output powers. The free variables could be $P_{i,A}(t), P_{i,B}(t), P_{i,C}(t)$ if phase powers are individually controlled, using a dedicated power converter, than the problem is 3-D.

MICROGRID CASE STUDY I

To explain proposed method, we investigate a power system suggested by Brekken et al.[16]. The power system [fig.5(a)] incorporates a wind farm (renewable energy source), linked with a battery storage energy . The energy stored in the battery during high winds. When the wind is low the stored energy is released, smoothing the total power inserted to the grid.

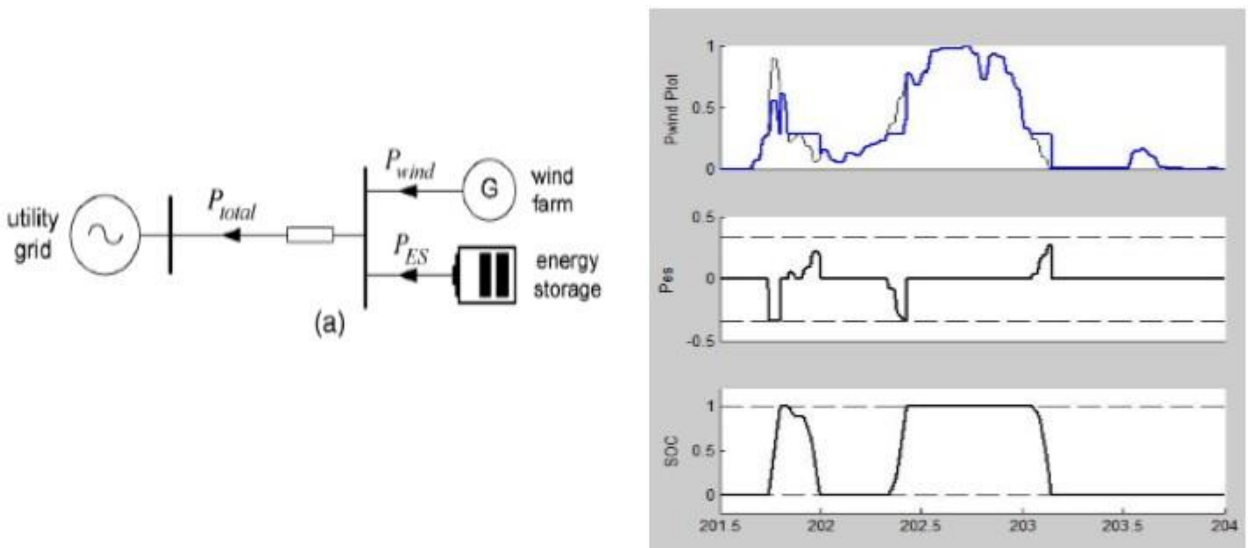


Fig.5.Brekken's et al Power System. [16]. (a) Storage and wind farm. (b) Optimal solution. Wind power and total power at the top. storage power at middle.Battery state of charge(SOC) at the bottom.

The below depiction is duplicated from the [16]: wind power is indicated by P_{wind}, total power is P_{total} and storage power is P_{ES} . The battery is modelled by its capacity power P_{rated}, the battery state of charge SOC in the range 0....1 and the storage capacity is J_{rated}. This indicates energy in this problem. The storage state equations are

$$\frac{d}{dt}SOC = -\frac{\eta \cdot P_{ES}}{J_{rated}}$$

$$\eta = \begin{cases} \eta_{out}, P_{ES} > 0 \\ \eta_{in}, P_{ES} < 0 \end{cases} \qquad (16)$$

$$-P_{rated} \le P_{ES} \le P_{rated}$$

$$0 \le SOC \le 1$$

The parameters are chosen as given below: $P_{rated} = 0.34, \eta_{in} = 0.85, \eta_{out} = 1.15$ and $J_{rated} = 0.4$.Wind power P_{wind} is sampled from [16].

The recommended dynamic programming analysis is adoptedto this system, optimizing the use of storage.A price signal is unavailable, so minimal price objective could not be computed. Instead we chose to optimize the output power of the system through minimizing the mutual power linelosses . Presuming a bus voltage $V_1 = 1.0$ and a resistance of R=0.01, the objective is

$$\int_0^T \left(P_{total} - \frac{R}{V_1^2} \cdot P_{total}^2 \right) dt \rightarrow \min \qquad (17)$$

The value function $V(\cdot)$ is defined on state of charge and time step. It has the objective as given below:

$$V(t, SOC) = \int_t^T \left(P_{total}(\tau) - \frac{R}{V_1^2} \cdot P_{total}^2(\tau) \right) d\tau \qquad (18)$$

With initial condition SOC(t)= SOC

The analysis is calculated on a numeric grid, using time step of dt =0.1h, and dE=d(SOC)=0.01. $V(\cdot)$ is computed through backward recursion, scanning every possible paths of state of charge (SOC) over time. After that the optimal function SOC(t) is constructed by using forward recursion. The fig. 5(b) shows the optimal power flow results.

MICRO GRID CASE STUDY II

Both nontrivial network and storage devices are combined in the second system case study. Both the storage device constraints and physical constraints are satisfied and hence the power flow optimized. The main objective is to optimize the cumulative price of the energy at the Point of Common Coupling (PCC) [5].

The network is shown in fig.(6), which is a medium voltage (MV) network. A central transformer at the PCC supplies this medium voltage, which ratings are : $V_1(t) = V_{in}(t) = 13.8$ kv, S_{nom} = 5 MVA. Using a base equal to the transformer ratings impedances are specified in per unit. Active power is limited at the Point of Common Coupling (PCC) by the transformer. $-5 \le P_1(t) \le +5$ MW

The micro grid consists of six loads (six is a capacitor bank),two storage devices and two generators.

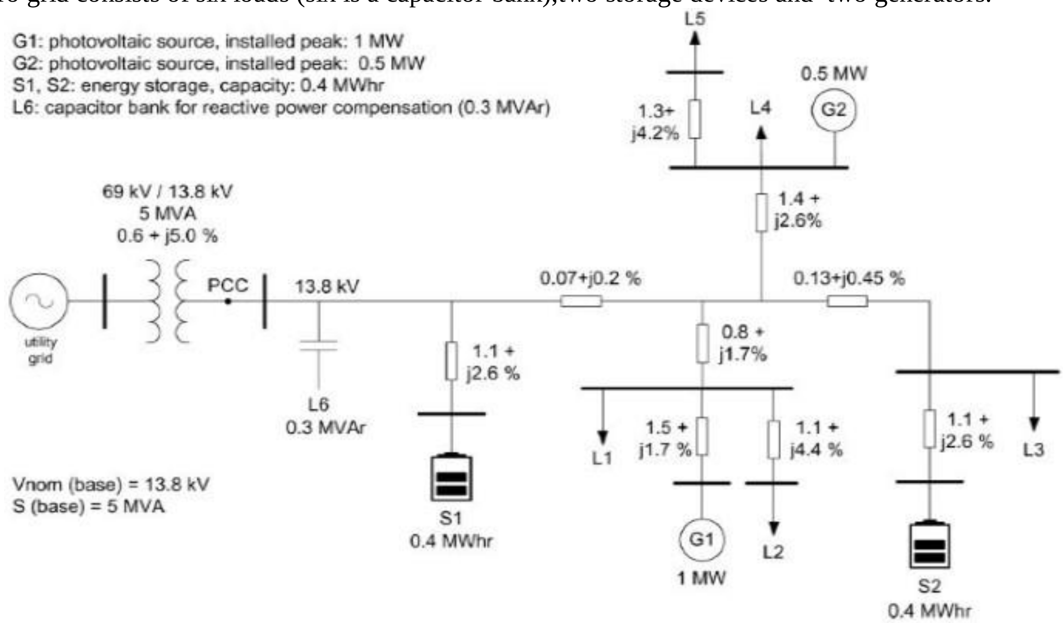


Fig.6. Microgrid case study II

The renewable generators are photovoltaic(PV) sources and having installed power peaks of 1 and 0.5 MW. They give only active power. Over a 72 hour period the power signals are generated as shown in fig. 7. Each storage device has a capacity of 0.4 MWhr. The storage state equations are given by

$$\frac{d}{dt}E_i = -\alpha \cdot E_i - \mu(P_i)\cdot P_i$$
$$\mu(P_i) = \begin{cases} \frac{1}{\eta_0}, P_i \geq 0 \\ \eta_0, P_i \leq 0 \end{cases} \quad (19)$$
$$0 \leq E_i(t) \leq E_{i,\max}$$

Where $E_{i,max}$ indicates device capacity, η_0 is the efficiency of the storage device and α is the rate of discharge. The parameters chosen are $E_{i,\max}$ =0.4 MWhr for each device, and α = 0.021/h. Efficiency η_0 is varying, taking the values η_0 =1.0,0.6, 0.4, and 0.1.

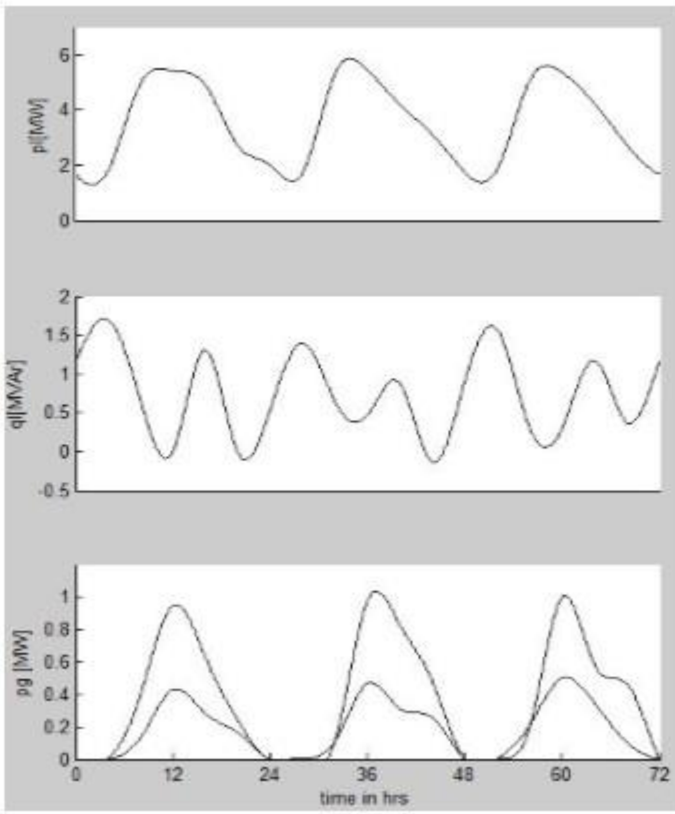


Fig.7. Microgrid case study II.Powers of the loads and generators.Top sum of the active power. Middle: sum of active and reactive power. Bottom: active power of the generators.

Using the 1-D process the power flow is optimized. The storage devices are treated as unified since the storage devices have the same ratings. Using backward recursion $V(t,E)$ calculated [(8)-(11)], with $dt = 0.5$ h, $dE = 0.05$ MWh. Using Gauss- Seidal analysis at each time step, the network power flow is solved. By utilizing forward recursion the optimal stored energy is rebuilt. The resulting power signals have shown in fig.8.

DISCUSSION

The work introduces an optimal power flow analysis, integrating storage devices. Due to numerical complexity of the problem, an exact global solution is not been shown so far, which includes both time domain and network domain. The conventional solvers look the problem as a function to be decreased. This type of thinking leads to conventional solution methods, like gradient search and linear programming. Anyhow, conventional solvers, like Newton-Raphson,

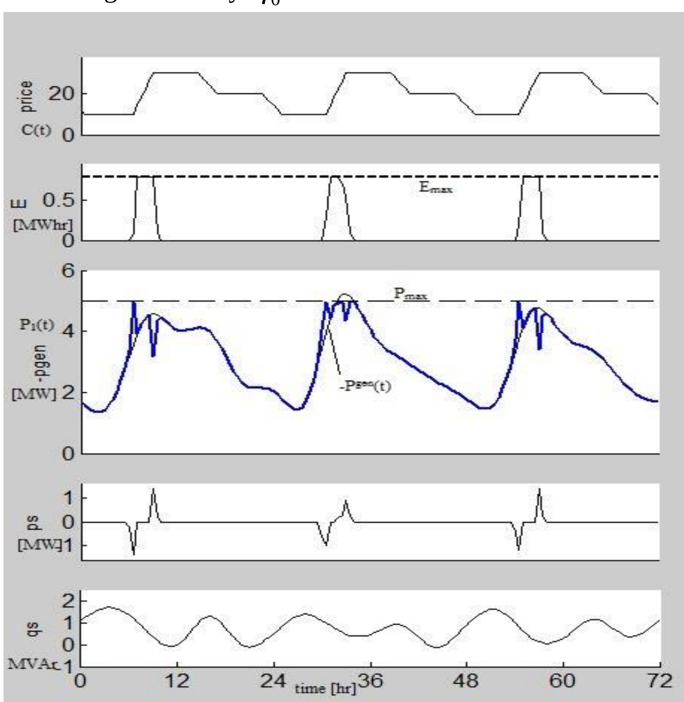
ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

are insufficient in the time domain (shown in section III). We introduce new approach of thinking, which prompt to an totally new different solution, which is capable of evade the numerical complexity. We consider the energystored as a resource to be allocated rather than looking the problem to be minimized within constraints. Instead of the minimization problem we see it as an allocation problem. To optimize power at the Point of Common Coupling (PCC) energy allocated in the time domain.

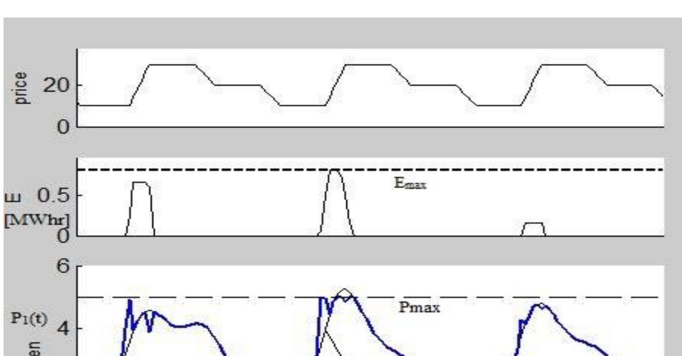
By using the dynamic programming algorithms, the allocation problems are easily solved, so this is the main “engine” of our solver. A recursive dynamic programming scanis associated in the solver, on time domain, with a conventional solver (we utilized Gauss-Seidal) on the network domain to optimize. For any topology of network (one –phase ,balanced,or unbalanced) the solution could be used since the solution process is general. In the same way, there is no presumption on the power flow solver, which could be Gauss-Seidal,Newton – Raphson, or a particular per-phase solver , like forward backward sweep or TCIM. At every time point, in respect to a earlier value the value function $V(\cdot)$ is computed. At every time point, the network power flow is solved, after replacing the storage devices with dummy $P-V$ sources. This power output is assessed by the present and previous energy values. Hence, each time point is assessed once. There is no need to recompute entire energy path, hence the calculation numerically efficient.

There are several important advantages by using dynamic programming approach. These are first, it concede the optimal solution globally, since the algorithm scans the total solution space. Second, the model is highly general. It never bind to a certain model or constraint. The state equations [(3) and (4)] depicts the storage devices. In the same network different storage devices with entirely different properties may be integrated. The single –phase networks are solved in the same way as three phase networks. The different objective functions could be considered [(5)-(7) and (17)]. The solution method is similar forever : a recursive scan of all the feasible system states.

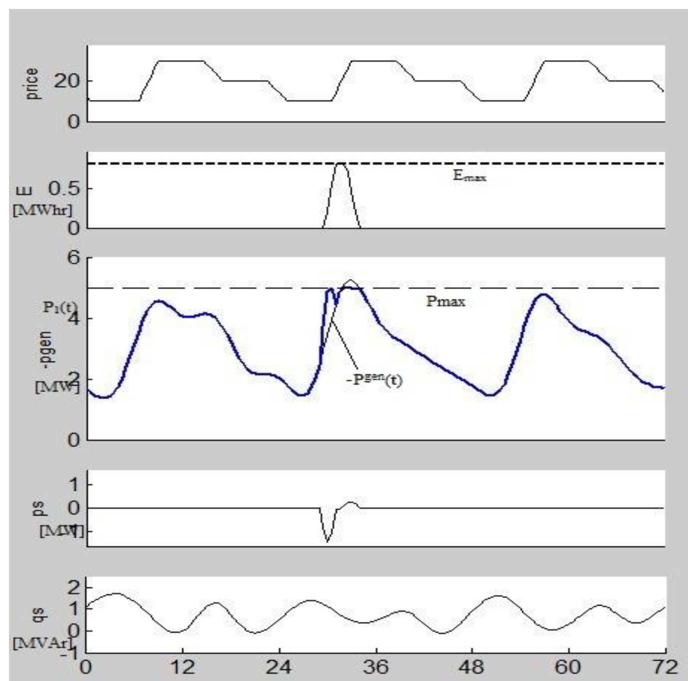
Storage efficiency $\eta_0 = 1.0$



(b) Storage efficiency $\eta_0 = 0.6$



(c) Storage efficiency $\eta_0 = 0.4$



(d) Storage efficiency $\eta_0 = 0.1$

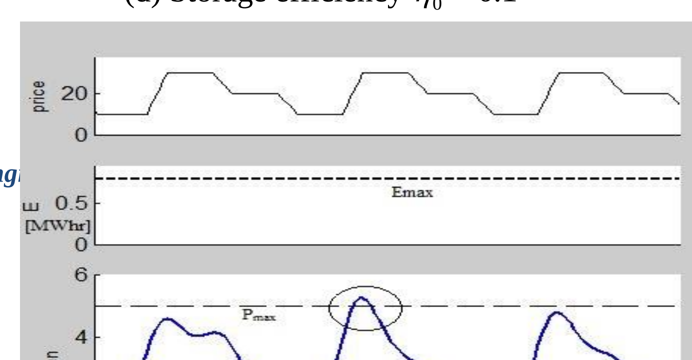


Fig.8.Microgrid case study II. Results of Optimal solution at different storage efficiencies (a) $\eta_0 = 1.0$ ***(b)*** $\eta_0 = 0.6$ ***,(c)*** $\eta_0 = 0.4$ ***,(d)*** $\eta_0 = 0.1$***. From the top to bottom the graphs*** $C(t)-$ ***price,*** $E(t)-$ ***stored energy,*** $P^{gen}(t)-$ ***the combined active power generation of loads and generators (taken negative),*** $P^{s}(t)-$ ***combined active power supplied by storage devices,*** $Q^{s}(t)-$ ***combined reactive power supplied by the storage devices***

A major drawback of the proposed approach is that numerical complexity increases in power law with number of (various) storage devices, which is evident in the fig.4(b): an extra dimension to the solution space is contributed by each storage device. From our experience, a network is evaluated in seconds with a single storage device. Anyhow, a system with four or five storage devices is evaluated, if it consists of only a less buses.

The case studies for two systems are shown. Two bus topology is shown in the first system (fig.5). Two renewable sources and two storage devices ate shown in the second system (fig.6). The system vary in both design objectivesand topology and utilize various storage devices. The goal in the initial system is to minimize the loss on transmission line, while in the second system is to decrease price of the energy imported. For both the systems the same dynamic programming is applied. The cost function $V(\cdot)$ is shown in (8), is defined and evaluated by backward recursion, as shown in equations (9)-(11). The optimal stored energy and power flow is given by forward recursion, which is described in (12).

The resulting optimal power management fig.5 and 8 affirms a similar conceptual strategy, for both the systems: according to the availability of primary source, this is wind power in the first example, orin the second example low cost energy at the point of common coupling(PCC). In the first example stored energy is released to network when the wind power is not available while in the second example it is when the tariff of energy is very high. Stored energy contribute to equalize the whole power, in order to decrease losses as much as possible, in both the systems. The second system consists of nonzero admittances of power lines and power limit of the transformer. The management of stored energy effected by this topology of the network. For example, to sustain the 5 –MVA capacity of the PCC's transformer, the storage device compensates the load, this is shown in fig.8(c). Fig. 8 shows the effect of storage efficiency (η_0) on power management. The storage device is charged to full capacity in fig.8(a), ($\eta_0 = 1$). Losses are higher and the storage device is not fully charged this is shown in fig.8(b), ($\eta_0 = 0.6$). In the fig.8(c), the storage device is very lossy that it become economically worthless. In the fig.8(d), ($\eta_0 = 0.1$),the storage losses prevails. Here, the storage device could not supply enough power to compensate the load's power peak , and the network become unstable. Hence there is no feasible solution.

CONCLUSION

This work proposes an algorithm to calculate the optimal energy management of storage devices in grid connected microgrids. Stored energy is controlled in order to balance the power flow of loads and renewable sources, on the time domain, minimizing the overall cost of energy at point of common coupling (PCC). The algorithm associates an arbitrary network topology, which could be general single phase, balanced, or unbalanced three-phase system. It utilizes a power flow solver in thenetwork domain, within a dynamic programming recursive search in the time domain. This combination is powerful and numerically efficient and discloses the globally optimal stored energy versus time for every storage device.

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