MITSUBISHI ELECTRIC RESEARCH LABORATORIES
http://www.merl.com

# Flex-grid:a dynamic and adaptive configurable power distribution system

Sun, H.; Wang, Y.; Nikovski, D.N.; Zhang, J.

TR2015-082 June 2015

**Abstract**

This paper proposes a new configuration ofdistribution system, Flex-Grid that dynamically and adaptively re-configures in real-time to maximally utilize the renewables, improve energy efficiency, reliability and power quality, particularly if the system includes distributed generations and energy storages. A multi-objective optimal scheduling method is provided to partition the system into self-sufficient sections through optimally combination of adjacent basic switching sections. The method uses two storage based transient security indices, storage compensation power margin and storage compensation energy margin to evaluate the transient stability margin of distribution system when subject to large unexpected load deviations. Numerical results on modified IEEE 123-node distribution test system are given to demonstrate the effectiveness of the proposed system.

*2015 IEEE PowerTech*

# Flex-Grid: A Dynamic and Adaptive Configurable Power Distribution System

Hongbo Sun, Yishen Wang, Daniel Nikovski and Jinyun Zhang
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139, USA

***Abstract*— This paper proposes a new configuration of distribution system, Flex-Grid that dynamically and adaptively re-configures in real-time to maximally utilize the renewables, improve energy efficiency, reliability and power quality, particularly if the system includes distributed generations and energy storages. A multi-objective optimal scheduling method is provided to partition the system into self-sufficient sections through optimally combination of adjacent basic switching sections. The method uses two storage based transient security indices, storage compensation power margin and storage compensation energy margin to evaluate the transient stability margin of distribution system when subject to large unexpected load deviations. Numerical results on modified IEEE 123-node distribution test system are given to demonstrate the effectiveness of the proposed system.**

***Index Terms*-- Distributed Generations, Distribution Systems, Energy Storages, Topology Reconfiguration.**

## I. INTRODUCTION

Conventional distribution systems are mainly fed from a main grid, use a radial configuration, and operate with unidirectional flows. The configurations of the systems are fixed, and with a "one-size-fits-all" reliability standards. Due to lack of local generation supports, such systems can be prone to wide-spread outages and slow restoration. They also have low efficiency, reliability and quality.

With increasing installation of renewable distributed generations (DG) and energy storages, there are more and more regions in distribution systems that enable local energy self-sufficiency at least for certain periods of a daily operation, provided the distribution system is properly designed to integrate the DGs and storages. This opens up new issues for the operation and control of the distribution systems. The first issue is that many of the renewable power sources are weather and time dependent. Therefore, the distribution system needs to be flexible to best facilitate intermittent and time-dependent renewable power source. In addition, the operation of the distribution systems needs to be able to accommodate more frequently flow direction variations. The second issue is that some renewable generation resources, such as solar panels are integrated with distribution systems through DC/ AC inverters. However, inverter based generation sources have no or less inertia than conventional synchronous generators. Thus, the distribution system has less time to react and to avoid instability when a local emergency event occurs. Therefore, the beakers and switches must be operate at much higher switching rate to reduce the system reaction time, and capacities of power storages must be properly used to increase the inertia of the system.

Several methods are known for configuring distribution systems to achieve a specific objective [1]-[4]. Those methods generally configure distribution systems for specific situations or applications, such as faults, and load balancing. Those solutions do not provide adequate solutions for distribution systems with a large number of renewable DG. Therefore, there is a need for a distribution system that can be configured dynamically to increase reliability, and efficiency of power distribution among consumers.

This paper proposes a new configuration of distribution system, Flex-Grid that can dynamically and adaptably configure a power distribution system in response to real-time changes in generation resources, load demands, system reliability and stability. Compared with a conventional distribution system, Flex-Grid may need larger investment cost in switching equipment and measurement. These investment will be well rewarded by maximally utilization of clean renewables, and higher energy efficiency and power quality under normal operations, and faster response to emergencies, less power outage, and quicker service restoration during emergency or fault conditions. The proposed configuration scheduling model considers both energy and power reserve/margin requirements for maintaining grid stable operation. The storages, and the main grid if needed, are used to provide the required power and energy reserves to meet the stability requirements for a system with increasing installations of fast inverter based renewable.

## II. CONFIGURATION OF FLEX-GRID

Fig. 1 shows an example configuration of a Flex-Grid. All conventional sectionalizing and tie switches in the distribution system are replaced with super-switches, e.g. solid-state switches. These switches can open and close at a relatively high frequently when compared with conventional electromechanical switches, and be equipped with phasor measurement units (PMU) to enable real-time monitoring and control. In Fig. 1, there are eight super-switches. The switches SS-1 and SS-8 are connected to the main grid. The PMU can supply voltages and currents measurements at high sampling rate, for examples, 60 samples per second.

Based on the location of super-switches, the distribution system can be partitioned into a set of basic switching sections (BSS). The BSS is a minimal section that the distribution system operators can operate or isolate. Adjacent BSSs can be combined into a self-sufficient section (SSS) that operates independently for each other. Each SSS has sufficient generation and storage reserve to maintain a stable frequency and voltage with appropriate stability margins. The SSSs can be re-configured in response to loading and sourcing changes, and emergencies through opening or closing the super-switches. The configuration changes can be based on monitoring and analyzing system states according to the real-time measurements by the PMU at the switches. The SSS in Fig. 1 is formed by opening the super-switches SS-1 and SS-3, and closing the super-switch SS-2.

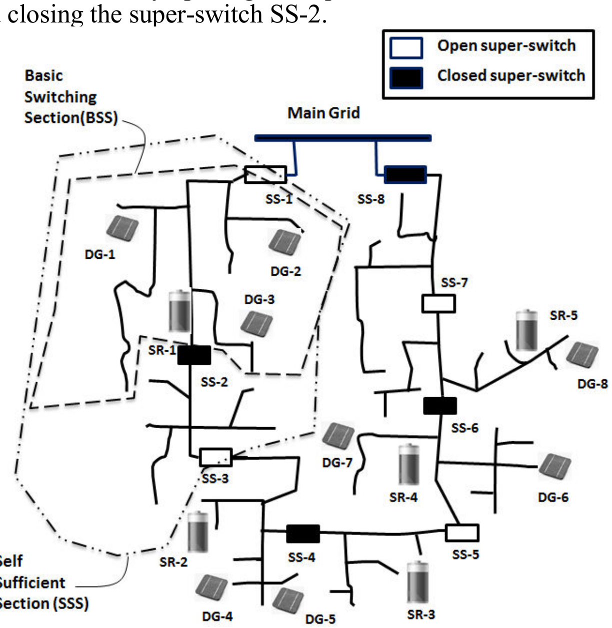


Fig.1 Example Configuration of Flex-Grid

## III. Operation of Flex-Grid

As an independent operated section, each SSS has adequate distributed generation capabilities to ensure a load generation balance. In addition, to reduce the maintenance cost and keep the system reliable, the super-switches should not operate too frequently, which means the load generation balance within each SSS should be consistent over a relatively longer period of time called an operation cycle. The topology should be valid for an entire operation cycle as long as there are no exceptional events that exceed certain constraints of an objective function. The Flex-Grid configures the distribution system dynamically and adaptively through a four-level process as shown in Fig. 2.

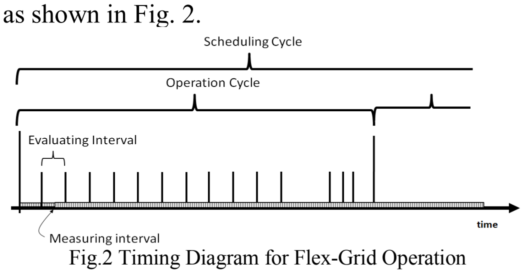


Fig.2 Timing Diagram for Flex-Grid Operation

At a finest level, a state of the distribution system is measured essentially in real-time, e.g., seconds or less. A dynamic state estimation and emergency detection are used to estimate the system status and identify or predict system emergences. An emergency event can automatically trigger a determination of configuration change. The measurements along generation and load forecast are evaluated periodically, e.g., using an evaluating interval of, for example, every couple of minutes, using power flow and stability analysis. Ideally, the configuration should satisfy security, stability, reliability and efficiency requirements during all evaluating intervals. An operation cycle is substantially longer than the evaluating interval, e.g., 30 to 180 minutes. The length of the operation cycle can be predetermined or set by the distribution system operator when and as needed. The goal of the longer operation cycle is to keep the configuration of the distribution system relatively stable unless constraints on an objective function that evaluates the performance of the system are violated. If the configuration is changed, then a new operation cycle starts. If there is a need for coordination of storage charging and discharging, and energy neutrality of load demand response for a much longer period of time, such as 24 hours, a scheduling cycle may be added on the top of operation cycles.

## IV. Determiniation of Optimal Configuration

An optimal problem is formulated to determine the open and close statues of super-switches in the distribution system. An optimal configuration candidate is determined according to multiple objective functions.

A minimization of system power loss over entire operation cycle, $I_{loss}$ is used to express the objective for energy efficiency, in which the power loss for any device between bus $i$ and bus $j$ on an available phase $m$ at evaluation interval $t$ is calculated as the sum of its active power flows at different directions, $P_{ij,m}^{t}$ and $P_{ji,m}^{t}$ :

$$I_{loss} = \sum_{t \in T} \sum_{ij \in DEV} \sum_{m \in PH_{ij}} \left| P_{ij,m}^{t} + P_{ji,m}^{t} \right| \tag{1}$$

$T$ is the set of evaluating intervals for the entire operation cycle, $DEV$ is the set of devices, and $PH_{ij}$ is the sets of available phases for device between bus $i$ and bus $j$.

The objective for power quality is expressed as a minimization of sum of system voltage violations against voltage thresholds over all evaluating intervals, $I_{violation}$ :

$$I_{violation} = \sum_{t \in T} \sum_{i \in BUS} \sum_{m \in PH_i} (\Delta \overline{V}_{i,m}^{t} + \Delta \underline{V}_{i,m}^{t}) \tag{2}$$

$BUS$ is the set of buses in the system, and $PH_i$ is the set of available phases for bus $i$. $\Delta \overline{V}_{i,m}^{t}$ and $\Delta \underline{V}_{i,m}^{t}$ are the voltage violations over the upper and lower voltage thresholds, $\overline{V}_{i,m}$ and $\underline{V}_{i,m}$.

A minimization of sum of overload ratios against the device capacities for all devices over entire operation cycle, $I_{overload}$ is used to express the objective for device security:

$$I_{overload} = \sum_{t \in T} \sum_{ij \in DEV} \sum_{m \in PH_{ij}} \Delta \overline{S}_{ij,m}^{t} \Big/ \overline{S}_{ij,m} \tag{3}$$

$\overline{S}_{ij,m}$ is the upper limit of apparent power flowing on the device between bus $i$ and bus $j$ , and $\Delta \overline{S}_{ij,m}^{t}$ is the overload at the device.

The objective for customer comfort and reliability is expressed as minimization of weighted sum of customer approved power reduction, and forced power curtailment, for the system over entire operation cycle, $I_{reduction}$ :

$$I_{reduction} = \sum_{t\in T}\sum_{i\in BUS}\sum_{m\in PH_i}(\alpha^t_{dr}P^t_{R_i,m} + \alpha^t_{cut}P^t_{C_i,m}) \quad (4)$$

$\alpha^t_{dr}$ and $\alpha^t_{cut}$ are the penalty coefficients for customer discomfort caused by voluntary power reduction, $P^t_{R_i,m}$ and loss caused by forced power shedding, $P^t_{C_i,m}$. The voluntary and forced load reductions can be regarded as valid measures for operators to balance the system, if the reductions are within their maximum and minimal capacities, $\overline{S}_{R_i,m}$ and $\underline{S}_{R_i,m}$ for a demand response, and $\overline{S}_{C_i,m}$ and $\underline{S}_{C_i,m}$ for a load shedding.

A minimization of weighted sum of the unutilized active powers of distributed generations, and purchased active powers from the main grid over all evaluating intervals, $I_{dependency}$ is used to express the objective for energy independency and renewable utilization:

$$I_{dependency} = \sum_{t\in T}\sum_{i\in BUS}\sum_{m\in PH_i}[\alpha^t_{main}P^t_{MG_i,m} + \alpha^t_{local}(\overline{P}^t_{DG_i,m} - P^t_{DG_i,m})] \quad (5)$$

$P^t_{MG_i,m}$ is the active power imported from the main grid. $P^t_{DG_i,m}$ and $\overline{P}^t_{DG_i,m}$ are the active power generated by distributed generators and its maximum capacity. $\alpha^t_{main}$ and $\alpha^t_{local}$ are the penalty coefficients for importing power from the main grid, and un-used powers from local resources.

The objective for super-switch operations is expressed as minimization of a weighted sum of the total number of switch open/close state change, powers flowing on the switches, voltage and phase angle mismatches between terminal buses of super switches, $I_{switching}$. The goals of this objective are to limit the un-necessary switching operations, restrain the un-necessary power exchanges between sections, and minimize the mismatches of voltages and phase angles between switch terminals. The last synchronization goal is required to enable the super-switch well prepared for immediate closing when needed.

$$I_{switching} = \sum_{t\in T}\sum_{ij\in SSW}\{\alpha^t_{sw}\left|x_{ij} - x^{(0)}_{ij}\right| + \sum_{m\in PH_{ij}}\alpha^t_{power}\left|S^t_{ij,m}\right| + \sum_{m\in PH_{ij}}[\alpha^t_{vol}\left|V^t_{i,m} - V^t_{j,m}\right| + \alpha^t_{ang}\left|\theta^t_{i,m} - \theta^t_{j,m}\right|]\} \quad (6)$$

$x_{ij}$ and $x^{(0)}_{ij}$ are the on/off status for the super switch between bus $i$ and bus $j$ for the whole operation cycle and its status before current cycle, where 1 denotes on and 0 denotes off. $V^t_{i,m}, \theta^t_{i,m}$ and $\theta^t_{j,m}, V^t_{j,m}$ are the voltages and phase angles for bus $i$ and bus $j$ respectively. $\alpha^t_{sw}, \alpha^t_{power}, \alpha^t_{vol}$ and $\alpha^t_{ang}$ are the penalty coefficients for switch operation, flow exchange, voltage magnitude mismatch, and phase angle mismatch.

A candidate configuration should satisfy a set of constraints derived from steady-state security, reliability, power quality, device technical limitations, and transient stability. For each bus, or a set of topology-connected buses, such as a basic switching section, the importing and exporting powers must be balanced for each phase, and each evaluation interval:

$$S^t_{MG_i,m} + S^t_{DG_i,m} + S^t_{R_i,m} + S^t_{C_i,m} + R^t_{DCH_i,m}\eta_{DCH_i,m} = \sum_{j\in DEV_i} S^t_{ij,m} + S^t_{D_i,m} + R^t_{CH_i,m}/\eta_{CH_i,m}, \quad i\in BUS, m\in PH_i \quad (7)$$

$S^t_{MG_i,m}$ and $S^t_{DG_i,m}$ are the apparent powers imported externally from the main grid, and generated locally by distributed generator. $S^t_{D_i,m}$, $S^t_{R_i,m}$ and $S^t_{C_i,m}$ are the complex powers of load demands, voluntary load reductions, and forced power curtailments. $R^t_{CH_i,m}$ and $R^t_{DCH_i,m}$ are the storage's charging and discharging rates, $\eta_{DCH_i,m}$ and $\eta_{CH_i,m}$ are the efficiencies of charging and discharging of storages. $S^t_{ij,m}$ and $S^t_{ji,m}$ are two directional power flows on the device between bus $i$ and bus $j$. $DEV_i$ is the set of buses that connected to bus $i$.

The power flows on a super switch, or other devices must be within its capacities. For any non-super-switch device, temporary overloads are allowed, but minimized by a penalty in the associated objective function as in (3).

$$\left|S^t_{ij,m}\right| = \left|S^t_{ji,m}\right| \le x_{ij}\overline{S}_{ij,m}, \quad ij\in SSW, m\in PH_{ij} \quad (8)$$

$$\max\{\left|S^t_{ij,m}\right|, \left|S^t_{ji,m}\right|\} \le \overline{S}_{ij,m} + \Delta\overline{S}^t_{ij,m}, \ ij\in DEV, m\in PH_{ij} \quad (9)$$

For a two-terminal device with impedances, the power flows on the device are determined according to the phase voltages at two terminal buses, and the branch admittance matrix for the device:

$$S^t_{ij,m} = V_{i,m}e^{j\theta_{i,m}}\sum_{n\in PH_{ij}}(Y^{AC-ij}_{i,m-i,n}V_{i,n}e^{j\theta_{i,n}} + Y^{AC-ij}_{i,m-j,n}V_{j,n}e^{j\theta_{j,n}})^*$$

$$S^t_{ji,m} = V_{j,m}e^{j\theta_{j,m}}\sum_{n\in PH_{ij}}(Y^{AC-ij}_{j,m-i,n}V_{i,n}e^{j\theta_{i,n}} + Y^{AC-ij}_{j,m-j,n}V_{j,n}e^{j\theta_{j,n}})^* \quad (10)$$

where, $Y^{AC-ij}_{j,m-i,n}$, $Y^{AC-ij}_{i,m-j,n}$, $Y^{AC-ij}_{j,m-i,n}$ and $Y^{AC-ij}_{j,m-j,n}$ are the elements of branch admittance matrix for the device, $Y^{AC-ij}$ at the row and column given by the subscript letters, in which the first twos give the corresponding bus and phase of the row, and last twos give the corresponding bus and phase of the column. The formulation of (10) has big impacts on the complexity of the optimal configuration model. In order to simplify the model, this full AC power flow equations may be replaced with more simplified ones, such as DC power flow for a balanced system.

The phase voltage for each bus should be within its normal thresholds that defined by technical and regulation requirements. Temporary voltage violations are allowed, but minimized by a penalty in the objective function in (2):

$$\underline{V}_{i,m} - \Delta\underline{V}^t_{i,m} \le V^t_{i,m} \le \overline{V}_{i,m} + \Delta\overline{V}^t_{i,m}, \quad i\in BUS, m\in PH_i \quad (11)$$

The generations imported from the main grid and generated by local distributed should be within the allowed maximum and minimum power limits, and the incremental increase or decrease between two consecutive intervals are also constrained by their ramp-up and ramp-down rates. The main grid can be constrained three phases as a whole, and the distributed generators can be constrained by per phase. The constraints are listed in (12) and (13). Because complex powers are used, and it is assumed that if a complex number is less than another one, both its real and imaginary parts are less than the corresponding parts for another one.

$$\underline{S}^t_{MG_i} \le \sum_{m\in PH_i} S^t_{MG_i,m} \le \overline{S}^t_{MG_i}, \ \sum_{m\in PH_i}(S^t_{MG_i,m} - S^{t-1}_{MG_i,m}) \le RU_{MG_i}\Delta t,$$

$$\sum_{m\in PH_i}(S^{t-1}_{MG_i,m} - S^t_{MG_i,m}) \le RD_{MG_i}\Delta t, \quad m\in PH_i, i\in BUS \quad (12)$$

$$\underline{S}^t_{DG_i,m} \le S^t_{DG_i,m} \le \overline{S}^t_{DG_i,m}, \ S^t_{DG_i,m} - S^{t-1}_{DG_i,m} \le RU_{DG_i,m}\Delta t,$$

$$S_{DG_{i,m}}^{t-1} - S_{DG_{i,m}}^{t} \le RD_{DG_{i,m}} \Delta t, \; i \in BUS, m \in PH_i \quad (13)$$

where, $\overline{S}_{MG_i}^{t}$, $\underline{S}_{MG_i}^{t}$ and $\overline{S}_{DG_{i,m}}$, $\underline{S}_{DG_{i,m}}^{t}$ are the maximal and minimal capacities of main grid and distributed generation. $RU_{MG_i}$, $RD_{MG_i}$ and $RU_{DG_{i,m}}$, $RD_{DG_{i,m}}$ are the ram up and ramp down rates for the main grid and distributed generator. $\Delta t$ is the duration of an evaluation cycle.

The voluntary demand response and forced load shedding are limited by its maximum allowed limits. Besides, for some demand response applications, there are also energy neutrality constraints over a given period of time.

$$\underline{S}_{R_{i,m}} \le S_{R_{i,m}}^{t} \le \overline{S}_{R_{i,m}}, \; \sum_{t \in T} S_{R_{i,m}}^{t} = S_{R_{i,m}}^{sch},$$
$$\underline{S}_{C_{i,m}} \le S_{C_{i,m}}^{t} \le \overline{S}_{C_{i,m}}, \quad i \in BUS, m \in PH_i \quad (14)$$

$S_{R_{i,m}}^{sch}$ is a required amount of allowed power reductions for the whole operation cycle.

The charging and discharging rates for a storage are limited by its technical capacities, and these capacities can be different between a normal operation situation, and emergency situation, such as when a transient instability event occurs. Its state of charge should be within its minimal and maximal limits, and its value at the end of operation cycle also may be required not less than a given value.

$$\underline{R}_{CH_{i,m}} \le R_{CH_{i,m}}^{t} \le \overline{R}_{CH_{i,m}}, \underline{R}_{DCH_{i,m}} \le R_{DCH_{i,m}}^{t} \le \overline{R}_{DCH_{i,m}},$$
$$\underline{SOC}_{i,m} \le SOC_{i,m}^{t} \le \overline{SOC}_{i,m},$$
$$SOC_{i,m}^{T} \ge SOC_{i,m}^{sch}, \qquad i \in BUS, m \in PH_i \quad (15)$$

$\overline{R}_{CH_{i,m}}$, $\underline{R}_{CH_{i,m}}$ and $\overline{R}_{DCH_{i,m}}$, $\underline{R}_{DCH_{i,m}}$ are the maximal and minimal charging and discharging rates for the storage. $\underline{SOC}_{i,m}$ and $\overline{SOC}_{i,m}$ are the maximal and minimal state of charge limits for the storage. $SOC_{i,m}^{T}$ is the required state of charge by the end of operation cycle. The state of charge for a storages is defined as:

$$SOC_{j,m}^{t} = SOC_{j,m}^{t-1} + R_{CH_{j,m}}^{t} \Delta t - R_{DCH_{j,m}}^{t} \Delta t \qquad (16)$$

For each self-sufficient section, it must satisfies a minimal stability margin requirement. The stability margin can be provided by local storages and the main grid. The requirement is divided into two components, one is for power requirement, and the other is for energy requirement:

$$SCPM^{s,t} \ge \underline{SCPM}, SCEM^{s,t} \ge \underline{SCEM} \qquad s \in SSS \quad (17)$$

where, $SCPM^{s,t}$ and $SCEM^{s,t}$ are the storage compensation based power margin, and energy margin for a self-sufficient section s at evaluating interval. $\underline{SCPM}$ and $\underline{SCEM}$ are minimal power and energy reserve requirement, SSS is the set of self-sufficient sections.

The above formulated model is a multi-objective mixed integer non-linear optimization problem. To solve this problem more effectively, the problem is first solved without stability constraints. After candidate solutions are obtained, then a stability analysis is performed for the candidates to ensure the final solution has at least minimal stability margins. The multiple objectives are first merged into one overall objective with corresponding weighting factor for each objective, $I_{overall}$:

$$I_{overall} = \beta_{loss} I_{loss} + \beta_{violation} I_{violation} + \beta_{overload} I_{overload} + \beta_{reduction} I_{reduction} + \beta_{dependency} I_{dependency} + \beta_{switching} I_{switching} \quad (18)$$

where $\beta_{loss}$, $\beta_{voilation}$, $\beta_{overload}$, $\beta_{reduction}$, $\beta_{dependency}$ and $\beta_{switching}$ are the weighting factors for objectives (1)~(6) respectively. Then a linear programming technique with branch and bound strategy is used to solve the problem. Since the number of super switches are limited and their statues are 0-1 variables, an integer solution can be easily obtained by applying "branch and bound" strategy after a linear solution was obtained with a few additional iterations. The constraints for AC power flow equations are also iteratively linearized around initial points to be used.

However, even with above simplification steps, the problem is still not easy to solve for a practical system. Another heuristic technique is also used for solving the problem. We first aggregate all loads, storage and generations within each basic switching section into one node. And then based on each BSS' power balance equations, trigger an optimization solution over a scheduling cycle to determine the status of super switches, storage charging and discharging, demand response coordination, and generation outputs for each operation cycle. After that, configure the network with the solution, and evaluate its performances against multiple objectives for each evaluation interval. A new solution with full model and constraints is only needed for problematic intervals, and those intervals can be solved sequentially. Such solution strategy might not find the global optimal solution, but at least find a good feasible solution in a reasonable time.

## V. Storage Based Transient Stability Evaluation

Most critical for a successful configuration change is the computational time, especially in response to an emergency. One of major computational burden is the stability margin evaluation. For a low inertia distribution system equipped with energy storage systems, its stability is heavily dependent on the storage participation in the system, and its disturbance mainly comes from unexpected load/generation drop or rise. Therefore, the transient stability margin of the distribution system is evaluated by examining the capabilities of storages in the system to withstand a sudden load drop/rise. The transient security indices are determined according to the power and energy margins of storage compensation capacities.

The distribution system may include both high-inertia generator such as rotational generator, or low-inertia generator such as fast inverter based generator with droop controller. When a load variation occurs in the system, this load change and corresponding storage contribution can be virtually allocated to each generator, then the dynamics of phase angles for a generator can be expressed as (19) for a rotational generator, or (20) for a fast inverter based generator controlled through a droop controller:

$$M_{G_i} \frac{d^2 \delta_{G_i}}{dt^2} = P_{M_i} - D_i \frac{d\delta_{G_i}}{dt} - \sum_{m \in PH_{i,m}} P_{G_{i,m}} + (\Delta P_{VS_i} - \Delta P_{VD_i}) \quad (19)$$

$$\frac{d\delta_{G_i}}{dt} = D_{P_i}(P_{G_i}^{REF} - \sum_{m \in PH_{i,m}} P_{G_{i,m}}) + \omega_0 + (\Delta P_{VS_i} - \Delta P_{VD_i}) \qquad (20)$$

where, $\delta_{G_i}$, $M_{G_i}$ and $D_i$ are the phase angle, the inertia of machine, and the damping ratio for a generator at bus *i*. $P_{Gi}^{REF}$ and $D_{P_i}$ are the reference for generation active power output, and droop slope of the active power-frequency droop controller. $\omega_0$ is the nominal angular frequency. $\Delta P_{VD_i}$ and $\Delta P_{VS_i}$ is the virtual sustainable load variation and additional virtual storage contribution at bus *i*. A sustainable load variation level can be set as within a pre-determined percentage of current load, for example ± 10 %. If the additional virtual storage participation power provides the mitigation for the unexpected large power disturbances, then the system can withstand a certain level of load variation without transient reliability issues. Ideally, if the virtual contributions of storages and load variations are canceled each other, the generator can maintain its rotor angle and speed almost constant after the sustainable load variation. Generally speaking, if the integration of storage and load variation over a period of time is zero for a high-inertia generator, or the sum of storage and load variation is zero for a low-inertia generator, the generator can maintain its speed unchanged, that is the transient stability is maintained.

Similarly, for a self-sufficient section, if the total virtual storages required by the load variations are within the capacities of existing storages and main grid (if connected to the main grid), then the section is stable. The surplus of storage capacities over the required amount of virtual storages are the stability margins. The storage compensation power margin for section *s* at interval *t*, $SCPM^{s,t}$ is defined as

$$SCPM^{s,t} = \min\{0, P_{S_{CH}}^{s,t} - P_{VS_{CH}}^{s,t}\} \text{ if charging}$$

$$SCPM^{s,t} = \min\{0, P_{S_{CH}}^{s,t} - P_{VS_{CH}}^{s,t}\} \text{ if discharging} \quad (21)$$

where $P_{VS_{CH}}^{s,t}$ and $P_{VS_{CH}}^{s,t}$ are the required virtual charging and discharging powers of storages for the self-sufficient section *s* at interval *t*, and calculated as:

$$P_{VS_{CH}}^{s,t} = \max_{b \in BSS^s} \Delta P_{D_{Drop}}^{b} ; P_{VSDCH}^{s,t} = \max_{b \in BSS^s} \Delta P_{D_{Rise}}^{b} \quad (22)$$

$BSS^s$ is the set of basic switching sections for self-sufficient section *s*, $\Delta P_{D_{Drop}}^{b}$ and $\Delta P_{D_{Rise}}^{b}$ are the predetermined load drop and increase. $P_{VS_{CH}}^{s,t}$ and $P_{VS_{CH}}^{s,t}$ are the remaining charging and discharging power capacities for the section *s* at evaluating interval *t*, and calculated as:

$$P_{VS_{CH}}^{s,t} = \sum_{i \in BUS^s} \sum_{m \in PH_i} \min(\overline{R}_{CH_{i,m}}, \frac{\overline{SOC}_{i,m} - SOC_{i,m}^{t}}{\tau_{sct} C_t})$$

$$P_{VS_{CH}}^{s,t} = \sum_{i \in BUS^s} \sum_{m \in PH_i} \min(\overline{R}_{DCH_{i,m}}, \frac{SOC_{i,m}^{t} - \underline{SOC}_{i,m}}{\tau_{sct} C_t}) \quad (23)$$

where, $BUS^s$ is the set of storage buses in the self-sufficient section *s*. $C_t$ is a conversion factor for converting a second into the time unit used for SOC calculation. $\tau_{sct}$ is a storage critical time parameter in seconds. This parameter is pre-determined and used as a measurement for the self-sufficient section to maintain stability for a reasonable period of time with disturbance, such as a large load variation. It can consider the relaying time, primary control action delay, control entering time, and disturbance clearing time. When the self-sufficient section is subject to a power shortage and lack of kinetic energy, the discharging power $P_{S_{DCH}}^{s,t}$ is used. When the section has excessive power and additional kinetic energy, the charging power $P_{S_{CH}}^{s,t}$ is used to absorb the additional kinetic energy.

The storage compensation energy margin for section *s* at evaluating interval *t*, $SCEM^{s,t}$ is defined as

$$SCEM^{s,t} = \min\{0, E_{SCH}^{s,t} - P_{VSCH}^{s,t} \tau_{sct}\} \text{ if charging}$$

$$SCEM^{s,t} = \min\{0, E_{SDCH}^{s,t} - P_{VSCH}^{s,t} \tau_{sct}\} \text{ if discharging} \quad (24)$$

where $E_{SCH}^{s,t}$ and $E_{S_{DCH}}^{s,t}$ are the charging and discharging energy capacities for the section *s* at evaluating interval *t*.

With adequate energy and power margins, the system can tolerate most unexpected load deviations and errors in forecasting renewable resources. The margins are a good measure of stability level of the distribution system without time domain analysis, so the method can be implemented in real-time. Extra conservativeness introduced by the storage compensation indices increases the stability guarantee.

## VI. NUMERICAL EXAMPLES

The proposed method has been tested on a 123-bus system that was adapted from the IEEE 123-node feeder [5].

As shown in Fig. 3, the IEEE 123-node feeder was modified to include multiple PV distributed generations, and storages. In addition, seven switches were changed into super-switches, including switches between nodes 150-149,18-135,13-152,151-300,60-160,54-94, and 97-197. Five nodes 13,47,76 and 101 were equipped with solar panels, and other five nodes were connected with storages, including nodes 7,36,58,105 and 72. It is assumed that the main grid uses conventional generations with ramp up/down rate of generation as 50% of rated capacity per minute, and distributed PV generations are fast inverter based with ramp up and down rates as 50% of rated capacity per second. The maximum charging and discharging power rate for a storage is 25% of rated power capacity per hour under normal operation, and 25% of rated power capacity per minute during emergency. The efficiency of charging and discharging are 95%. All unbalanced devices were replaced with three phase ones, and unbalanced loads are also re-allocated evenly to three phases. Accordingly, the system can be regarded as balanced, and reactive powers can also be ignored.

The 24-hour load profiles and PV generation profiles are used to dynamically configure the system with respect to load and generation daily variations. The durations for a operation cycle, and a scheduling cycle are set to be one hour and 24 hours respectively. Fig. 4 give the normalized daily load profile and PV generation profile that used for all loads and distributed resources in the system. The sampling rate is once per 3 minutes. The horizontal axis and vertical axis represent the accumulated number of intervals, and scaling factors for loads and active-power generations respectively.

Base on the locations of super switches, the system can be partitioned into 6 basic switching sections, sect-1,-2,-3,-4,-5 and -6. Sect-1 is connected to the main grid, and imports external generations to the local network. Other 5 sections solely use local generations and storages, including sect-2,-3,-

4-5 and -6.Table I and II gives the test results for dynamically re-configuring topology with respect to load and generation variation. Table I lists the detailed super-switch operation actions during the course of 24 hours. There are 8 different configurations for the entire day. During the nighttime hours, switches are not changed frequently. In contrast, they are changing more frequently during the daytime hours. Table II lists the configured self-sufficient sections that operated independently for each other. It is interesting to see that the frequency for self-sufficient section changes are less than the switches, and it is 5 times as shown in the table.

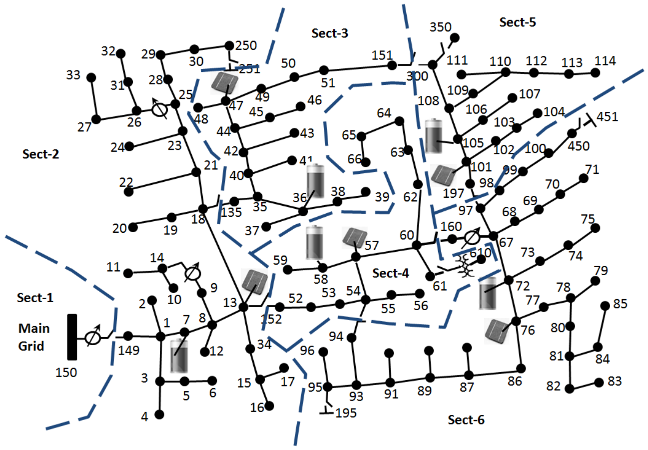


Fig.3 Modified IEEE 123-node feeder

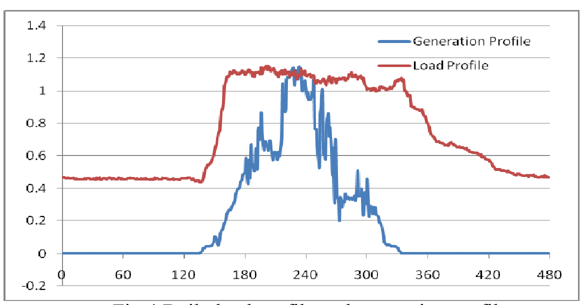


Fig.4 Daily load profile and generation profile

TABLE I
SUPER-SWITCH OPERATION SCHEDULE FOR 24 HOURS

| Config. | Hours | Super-switch Status | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 150-149 | 18-135 | 13-152 | 151-300 | 60-160 | 54-94 | 97-197 |
| 1 | 16-23,0-8 | 1 | 1 | 1 | 1 | 0 | 1 | 0 |
| 2 | 9 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |
| 3 | 10 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 4 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 5 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 13 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 14 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 8 | 15 | 1 | 1 | 0 | 1 | 0 | 1 | 1 |

The test results showed that for a system with higher penetration of renewable such as solar panels, there exists distinct difference of configuration between daytime operation, and nighttime operation. For a daytime configuration of a distribution system, it may have more self-sufficient sections that operated independently to fully utilize renewable resources. A self-sufficient section may have enough generations from its local resources, so it is disconnected from the main grid and other SSSs by opened corresponding super-switches at its boundaries. Some of these sections may solely use local resources, and set power storage units, e.g., batteries, at charging states to fully utilize the renewable resources. Meanwhile, we can have a nighttime configuration for the same distribution system. This configuration may have multiple independent-operation sections as well, but most of them may be connected with the main grid due to lack of local resources, and the storage units can also be used by setting at discharging states.

TABLE II
TOPOLOGY CONFIGURATIONS FOR SELF-SUFFICIENT SECTIONS

| Config. | Self-sufficient Sections | Connected with Main grid |
|---|---|---|
| 1,2,7,8 | 1 self-sufficient section, included all 6 available basic switching sections | Yes |
| 3 | 1 self-sufficient section including 5 local basic switching sections, but disconnected from the main grid. | No |
| 4 | 4 self-sufficient sections, sect-2,-3 and -4 are operated individually, and section -5 and -6 are combined together to operate. | No |
| 5 | 5 self-sufficient sections, all 5 local sections are operated individually. | No |
| 6 | 4 self-sufficient sections, sect-2,-3 and -5 are operated individually, and section -4 and -6 are combined together to operate. | No |

## VII. CONCLUSIONS AND FUTURE WORK

The increasing use of renewable generations, and utility-scale storages require that distribution systems be configured and operated in a manner that is different from the past. The proposed new configuration of distribution system, Flex-Grid enables the system to more efficiently utilize the distributed generations and storages through dynamically and adaptively configuring the system to respond to changes in load, source, and system conditions to increase energy efficiency, system reliability, and power quality of distribution systems.

This paper presents the preliminary results of our research on the configuration scheduling for a Flex-Grid under normal operation. Several issues may need future investigations, such as more efficient and accurate solution technique for configuration scheduling of practical systems, better control and coordination strategy for faults and emergency situations, and fast dynamic state estimation and prediction.

## REFERENCES

[1] M. Baran, and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” IEEE Trans. Power Deliv., vol. 4, no. 2, pp. 1401–1407, Apr. 1989.
[2] C. Ravera, A. Rebora, A. Taffone, S. Tenconi, and F. Zanzi, “Reconfigurable power distribution network”, US Patent application 20070086123 A1, Apr. 19, 2007.
[3] E.M. Carreno, R. Romero, and A. Padilha-Feltrin, “An efficient codification to solve distribution network reconfiguration for loss reduction problem,” IEEE Trans. Power Syst., vol. 23, no. 4, pp. 1542–1551, Nov. 2008.
[4] B. Amanulla, S. Chakrabarti, and S. N. Singh, “Reconfiguration of power distribution systems considering reliability and power loss,” IEEE Trans. Power Deliv., vol. 27, no. 2, pp. 918–926, Apr. 2012.
[5] IEEE PES. (2010, Sept.) Distribution test feeders. [Online]. Available: http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html.