SoftGrid: A Green Field Approach of Future Smart Grid

Yayun Zhou[1], Harald Held[1], Wolfram Klein[3], Kurt Majewski[2], Rainer Speh[4],
Philipp Emanuel Stelzig[3] and Christoph Wincheringer[1]
[1]*Siemens AG, Corporate Technology, RTC AUC MST-DE, Otto-Hahn-Ring 6, Munich, Germany*
[2]*Siemens AG, Corporate Technology, RTC BAM ORD-DE, Otto-Hahn-Ring 6, Munich, Germany*
[3]*Siemens AG, Corporate Technology, RTC AUC MSP-DE, Otto-Hahn-Ring 6, Munich, Germany*
[4]*Siemens AG, Infrastructure & Cities Sector Strategy, IC ST TI, Otto-Hahn-Ring 6, Munich, Germany*

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Abstract: In this paper, a novel power grid solution "SoftGrid" is proposed, which is a decentralized power system with two-level control architecture. The basic unit of this grid solution is a so-called SoftGrid-Adapter (SGA), which controls generators, consumers as well as energy storage devices under the guidance of an optimization model. The energy transmission among SGAs is supervised by a SoftGrid-Dispatcher (SGD), which balances energy among SGAs. Using the proposed SoftGrid two-level control architecture, one can build up a local grid from scratch. It is especially well-suited to be applied in remote areas where no commercial power grid exists. Hence it is also viewed as a green field approach to a future smart grid. The concept of SoftGrid is verified through system modeling and simulation under different scenarios. The simulation results show that SoftGrid is a power grid solution with both flexibility and reliability.

1 INTRODUCTION

Today's alternating current (AC) power grid is based on Nikola Tesla's design published in 1888 (Tesla, 1888). At that time, the grid was conceived as a local grid with a demand-driven control function. Those electricity systems were usually operated locally by cities or industries. As power grids grew over time, some of them were interconnected for economic and reliability reasons in the early 20th century. After several decades' development, the electric grids in developed countries have become very large and highly interconnected. In such grid systems, the power is generated in "central" generation power stations and delivered to major load centers to provide power to smaller industrial and domestic users over the entire supply area. In such centralized power system, the number of power stations had to increase in order to satisfy the increasing user demand. When the increasing number of power stations cannot keep up with the increasing demand of users, it results in poor power quality including blackouts and power cuts. Since the user demand varies from time to time, the grid capacity designed to meet the peak time demand usually leads to idle resources in average time. It remains as one of the limitations of the traditional electrical grid until the improvements of electronic communication technology finally provide a possibility to guide user demand in early 21st century. At that time, the intension to integrate highly variable renewable energy such as wind power and solar power into the existing grid leads to the need for more sophisticated control systems. Herein, the concept "smart grid" (Siemens, 2012) becomes very popular for it allows for systematic communication between suppliers and consumers and permits both the suppliers and the consumers to be more flexible and sophisticated in their operational strategies. Fig. 1 shows the evolutionary process of power grids. The move from a traditional grid to a smart grid is a move from a centralized, producer-controlled network to a less centralized and more consumer-interactive network.

Researches and market reports have shown that the upgrade from traditional grid to smart grid can bring in substantial benefits such as improvement of reliability by reducing power quality disturbances; improvement of efficiency by reducing the cost to produce, deliver, and consume electricity; protection of environment and reduction of emissions by integrating renewable energy resources; improvement of safety and security by reducing the probability and consequences of man-made attacks and natural disas-

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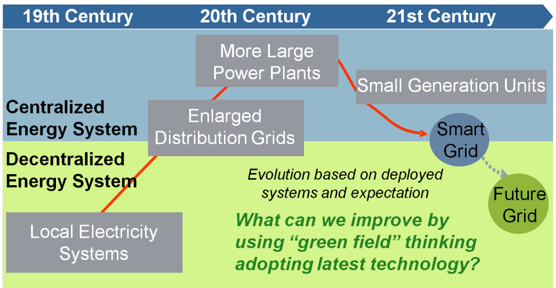

Figure 1: Evolutionary Process of Power Grids.

ters (Dodrill, 2010). Nevertheless, current smart grid projects are mostly carried out in developed countries to modernize their grid systems. There is still a market vacancy in remote areas and less developed countries, where no commercial grids are available. In those areas, the population density is often low and residents usually live far from each other. Since long distance transmission brings in energy losses, a more reasonable solution is to employ power generation and energy storage at a local level. This distributed generation concept allows collection of energy from many sources, providing higher power reliability and security with fewer environmental consequences compared with traditional power generators. However, application of individual distributed generators can cause many problems. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "microgrid" (Lasseter and Mettam, 2004)(Mohamed, 2008).

Similar to "microgrid", our power grid solution aims to serve decentralized systems. It does not rely on the existing commercial grids and is able to operate in a stand-alone mode. The basic unit of SoftGrid is a SoftGrid-Adapter (SGA), which controls generators, consumers and energy storage devices of typically a household or a small business under the guidance of an optimization model. It balances the power supply capacity and user demands by scheduling generation and consumption at a local level. Those basic units can connect with each other, building up a grid from bottom to up. Therefore, SoftGrid is especially applicable in remote areas with no existing energy grid. Moreover, it provides the option for stepwise investments and installations, starting with a single SGA, adding others and interconnecting them to a local executable grid. The energy transmission among SGAs is supervised by a SoftGrid-Dispatcher (SGD), which balances both the energy supplies and demands in this local network. Furthermore, the SGD regulates the power flow and enables the local grid to be integrated to an available external power grid. Fig. 2 shows the two-level control architecture of SoftGrid. With this two-level control architecture, SoftGrid combines the advantages of smart grid and microgrid, providing a reliable and flexible local grid which optimizes the power flow through sophisticated optimization models.

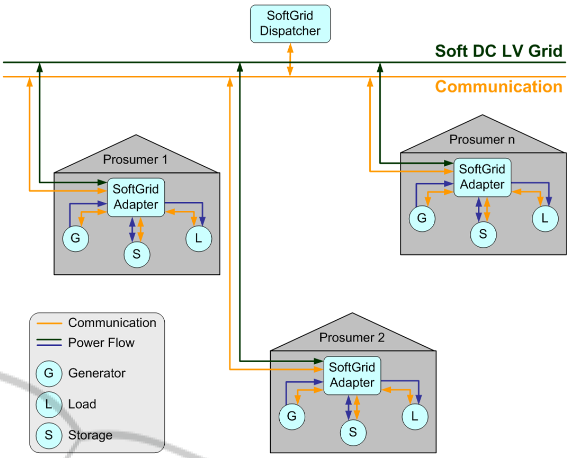

Figure 2: Two-level Control Architecture of SoftGrid.

In this paper, the concept of SoftGrid is proposed and verified through components modeling and user demand simulation under different scenarios. The rest of the paper is organized as followings: Firstly, the system model of SoftGrid is introduced in Section 2. The component models in a SoftGrid system are implemented and stored in a library in the CoSMOS (Complex Systems Modeling, Optimization and Simulation), which is a simulation and optimization software developed by our group[1]. Then the software structure of SoftGrid is briefly introduced in Section 3. It is developed based on the server-client architecture. Afterwards, the principles of the optimization model construction in the SGA and the SGD are revealed in Section 4. The optimization problems are solved by the CoinOR Solvers Ipopt and CBC (COIN-OR, 2012). To verify the concept under different operation environments, different examples are tested. Some simulation results are shown in Section 5. Finally, a conclusion is drawn in Section 6.

2 SYSTEM MODEL

A SoftGrid system comprises five categories of components: generator, consumer, storage device, control device and assistant component. The generator category not only includes renewable energy devices, such as photovoltaic panels, biomass genera-

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[1] Siemens AG, Corporate Technology, Research & Technology Center, Research Field Automation & Control, Research Group Simulation Germany

tors and wind turbines, but also allows the possible use of traditional energy resources, such as diesel generators. The generator models refer to (Mohamed, 2008)(Gonzalez-Longatt, 2006)(Jurado et al., 2003). The various electric consumption devices in a household are further categorized into three types: fixed-profile consumer, deferrable consumer, and energy-control consumer. The fixed-profile consumer operates according to a load profile that models the user demand with respect to time. Most household appliances can be modeled as fixed-profile consumers, such as light, refrigerator, television and fan. The deferrable consumer has a user-defined operation pattern and the operation time can be shifted within a certain time period. Typical example of a deferrable consumer are washing machine and dishwasher, whose operation pattern is pre-programmed (typically fill, wash, spin or fill, wash, heat) and the start of operation time can be optimized to minimize the cost or maximize the energy usage. The energy-control consumer is a device which transforms the electric energy into another form in order to store the energy or use it for certain purpose. A typical example of an energy-control consumer is water pump that pumps water to a tank or an irrigation device.

indent The usual storage device in the SoftGrid system is a battery. It is critical to balance the electricity demand and electricity supply to prevent deep discharge of the battery and idle resources caused by a full battery. Hence, a circuit based battery model is adopted and simplified according to the simulation need (Salameh et al., 1992)(Appelbaum and Weiss, 1982). A SoftGrid system has two types of control devices: SGA and SGD. SGA is the first level control device, which controls the operation of generator, and consumers with while monitoring the battery state of charge (SOC). It optimizes the energy allocation based on demand prognosis and power generation capacity prediction. SGD is the second level control device, which monitors the energy generation and consumption status in the local SGAs. Once energy shortage is foreseen in one of the interconnected local SGAs, the SGD will command other SGAs with energy residual to support the SGAs with energy shortage in order to keep the user demands satisfied in the whole system. The objective function of SGD fulfills the function to satisfy user-demands, charge storage devices, as well as minimize the transmission loss. The assistance components are the components that complete the system configuration, such as electric transmission line, resister and DCDC-Converter. All the component models are implemented and stored in a library.

Fig. 3 shows some components implemented in the SoftGrid library. In this library, each system component corresponds to a unique graphic symbol. The component model is implemented independently and connected later to constitute a complex system. New components can be added to the SoftGrid library in case of system extension. Each component provides a user interface that enables the user to set and change parameters. Fig. 4 shows an example of parameter setting menu of a component. Those components are the basic elements. Different test scenarios are constructed by changing grid topology and component parameters.

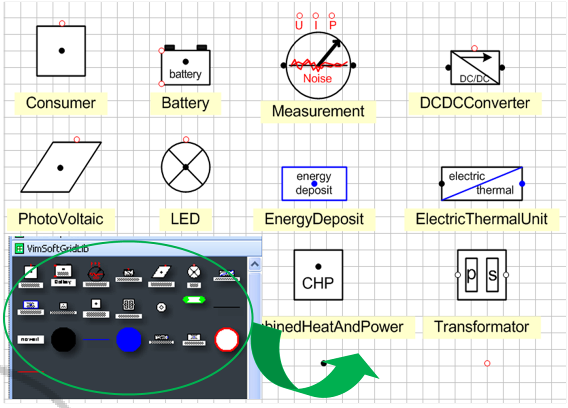
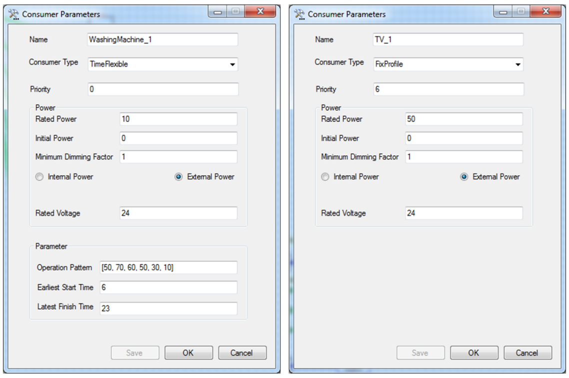


Figure 3: Some Simulation Component Models implemented in the SoftGrid System.


Consumer Parameters

Name: WashingMachine_1
Consumer Type: TimeFlexible
Priority: 0
Power
Rated Power: 10
Initial Power: 0
Minimum Dimming Factor: 1
○ Internal Power ● External Power
Rated Voltage: 24
Parameter
Operation Pattern: [50, 70, 60, 50, 30, 10]
Earliest Start Time: 6
Latest Finish Time: 23

Consumer Parameters

Name: TV_1
Consumer Type: FixProfile
Priority: 6
Power
Rated Power: 50
Initial Power: 0
Minimum Dimming Factor: 1
○ Internal Power ● External Power
Rated Voltage: 24

Figure 4: User Interface of Consumer.

3 SIMULATION SYSTEM

The SoftGrid system is implemented under the framework of CoSMOS (Complex Systems Modeling, Optimization and Simulation). It is a simulation tool developed by our group to simulate and optimize complex systems in different application areas. CoSMOS is a model based simulation tool with a client-server architecture. The components in a complex system are associated with mathematical models (typically partial differential equations (PDEs) and algebraic equations). Each component contains four parts: terminals, equations, parameters and extern-system-variables. Terminals are used to connect other components, for example in an electrical or control manner, in order to generate a system. From a mathematical point of view, when two components are connected, certain equations are formed. Those equations stand for the component model. Each component is characterized by different parameters and extern-system-variables are used to exchange data between different clients through the server.

Fig. 5 shows the software structure of the SoftGrid simulation system. The SoftGrid component library stores all components which are implemented according to system models introduced in the previous section. The chosen components are connected to set up a local grid network. In a SoftGrid test, three main processes are evolved: simulation, optimization, and automation. The simulation solves the electric network system and simulates the power flow inside the local network. The optimization serves as a headquarter deciding the power allocation for each component. The automation keeps the system robust against unexpected situations, such as sudden weather change and device failure. The PowerBridge is a decentralized communications unit, which enables operators of solar or wind power facilities to logon to a virtual power plant through the Internet with just a few mouse clicks.

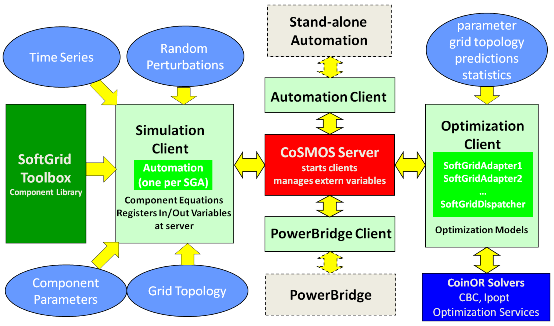


Figure 5: Software Architecture of SoftGrid System.

In the simulation process, the electricity demands are modeled as stochastic time series, which mimic the random behavior of users. The environmental impact is also considered as a stochastic process. The expectation value of the time series are used in the optimization process as predictions of electricity demands and electricity supplies. An automation process checks the status of energy storage devices in order to keep the system stable. The communication between these three processes is carried out by the corresponding clients. Fig. 6 shows the synchronization of these three processes.

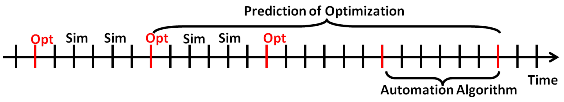


Figure 6: Synchronization of Simulation, Optimization and Automation.

4 OPTIMIZATION MODEL

There are two types of optimization problems in the SoftGrid system. In the basic control unit SGA, the key purpose is to keep a performance balance between the different consumers and generators connected to the local SGA and exploit all available energy as efficiently as possible. In the second level control unit SGD, the local system stability is maintained by allowing power transmission among SGAs. The task for the SGD is to guarantee the satisfaction of all user demands, maintain the system stability and minimize the transmission losses considering the local grid topology and network condition. The optimization problem is constructed based on a business inspired model and the objective function varies due to different scenarios and requirements. However, there are some basic principles about the optimization model construction:

- SGD Optimization. On a grid level, the SGD optimization collects information from the SGAs constituting the SoftGrid, including battery SoC and a cumulated energy consumption/generation prediction over a time-discrete prognosis horizon. It is assumed that the network topology in the SoftGrid is known (as it is constructed from scratch) and therefore one can compute the admittance matrix to incorporate the significant cable losses in the low voltage DC SoftGrid. The SGD optimization now computes for each single SGA and each interval of the time-discrete prognosis horizon optimal power inflows or outflows into the SoftGrid, taking into account transmissions losses and moreover additional generation capacities in the SGAs like diesel generators that the SGAs can dispatch in the case of necessity. Here, optimality means that power demands are met, diesel generator costs are avoided, batteries are charged, and resistive cable losses are minimized, as good as possible. Finally, the SGD is a purely continuous optimization problem and can be solved efficiently.
- SGA Optimization. The optimization on the local level guides the consumers connected to the SGA, its generators and monitors the battery SoC. More precisely, over the same time discrete prognosis

horizon the SGD uses the SGA optimization computes for each of its connected consumers as well as for the generators it can control (e.g. a diesel generator, opposed to a photovoltaic panel that generates power according to solar irradiance) a control signal, while it has to satisfy the power inflow/outflow the SGD imposes on the single SGA. The nature of these control signals depend on the nature of the consumers and generators. For deferrable loads with a fixed operation pattern, binary signals decide about whether the load is turned on or off in a certain used-defined time window of the time-discrete prognosis horizon. For energy-control loads and controllable generators a binary variable controls whether the machine is turned on or off during a certain user-defined time window of the prognosis horizon, while a continuous variable decides about the power with which the machine shall run (taking into account the machine's technical operation range). For profile-type loads, a continuous variable decides about dimming (again within the loads technical limits) while in case of insufficient power supply or a low battery a binary variable may switch the profile load off in every time interval. Also, consumers may be associated a priority such that the demands of high priority consumers are satisfied prior to those of low priority, which may in extreme cases be completely switched off by the optimization. When neglecting transmission losses between the SGA and its connected components (which are spatially close to the SGA), the resulting optimization problem has the form of a mixed integer linear program (MILP), which can be solved efficiently on an embedded computer even for realistic problem dimension.

In the end, we are able to separate the two optimization problems to two categories: The SGA optimization is modeled as a mixed integer linear programming (MILP) problem, which is solved by the CBC solver (CBC, 2012). The SGD optimization is modeled as a nonlinear programming (NLP) problem, which is solved by the Ipopt solver (Ipopt, 2012). This split into a purely continuous optimization model for the SGD and a mixed integer linear program for the SGA has several advantages. Firstly, it avoids solving a large mixed-integer nonlinear program that otherwise would guide all consumers and generators in the entire SoftGrid including the SGAs and their components. Moreover, since the optimal guidance for an SGA's components is done locally, i.e. solved on the SGA's embedded hardware, the system is more robust towards failure in the computation or in the computing hardware: even if the dispatcher or a single SGA fails to deliver results, the other problems may still be solved independently.

5 SIMULATION RESULTS

In order to verify the concept and find out appropriate system configuration parameters, different scenarios have been tested. Fig. 7 shows the stand-alone mode of a single SGA. This example shows a household with typical home appliances like television, refrigerator and washing machine. In this case, the refrigerator is a fixed-profile consumer, which needs to operate all time, while the washing machine is a deferrable consumer, which can be scheduled to operate in an appropriate time window to gain certain flexibility. The operation of LED and television are simulated by stochastic time series, and the expectations are passed to the optimization model as prognoses. Fig. 8 shows the electrical appliances' behavior for one day. It can be seen that the SGA can satisfy the user demand by allocate the power properly. Under the guidance of the optimization in the SGA, the washing machine is turned on at noon, when the electricity supply is sufficient due to the high solar irradiance thus large photovoltaic power generation and electricity consumption peak has not arrived yet. In order to check the robustness of the optimization model, a series of tests are carried out using different time series. In our tests, the optimization algorithm shows very good performance to keep the user demands satisfied. Only in very few occasions, some LEDs are dimmed in order to save energy.

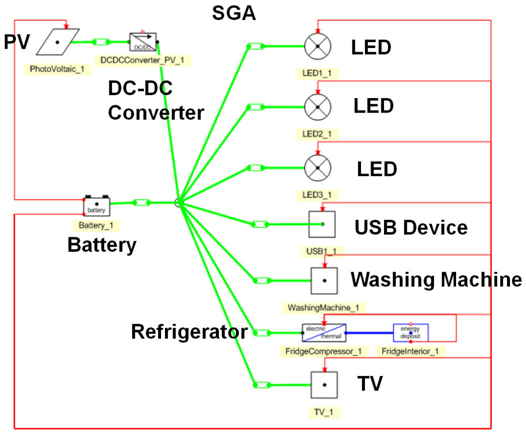


Figure 7: Test Scenario 1: Stand-alone SGA with Fixed-profile and Time-deferrable Consumers.

As introduced in Section 2, SoftGrid has two-level control architecture. Fig. 9 shows an example with three SGAs and one SGD. In this case, no external

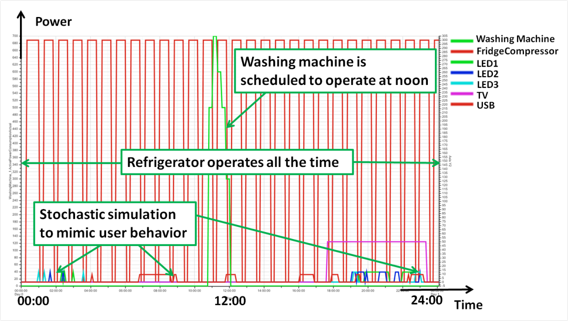


Figure 8: Power Consumption of Consumers.

grid is provided. This example is to test the performance of a SGD optimization algorithm. Each local grid controlled by the SGA contains one battery, one photovoltaic panel and several consumers. This system performance depends strongly on the local weather condition. Besides, we also investigate the system in a special condition. In the first SGA, we set up a battery with big capacity and a photovoltaic with low power production ability. In the second SGA, both parameters of battery and photovoltaic capacity are chosen to be medium. In the third SGA, we use a battery with a small capacity and a photovoltaic with high peak power generation. The optimization in the SGD has to balance this uneven system configuration.

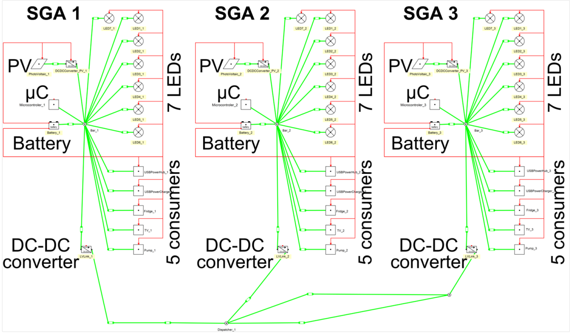


Figure 9: Test Scenario 2: 3 SGAs and 1 SGD.

Since there is no deferrable load and no biomass generator in the local grid, the SGA has little freedom in optimization. Without the SGD optimization, the SGA has troubles to run in the stand-alone mode. Obviously, the battery can only get charged at daytime. Even if the first battery has sufficient initial level, it does not get enough refills due to the small photovoltaic panel in the local system. Therefore, the user demands in the following days cannot be fulfilled. On the other side, the third battery is too small to store the energy generated by the photovoltaic during the daytime, which causes resource waste. The optimization algorithm running in the SGD allows power flow among the neighboring SGAs. It can balance the supply and demand globally. Fig. 10 shows the comparison of battery status with and without SGD optimization. We see that during the daytime extra energy generated by the third photovoltaic panel is transmitted to the first battery, while in the night the third SGA with small battery gets support from the first SGA to fulfill the user demands. In such a way, the three SGAs can balance the supply and demand by supporting each other. Fig. 11 shows the power transmission among SGAs, the positive power flow means that a local SGA receives power while the negative power flow means a local SGA exports power.

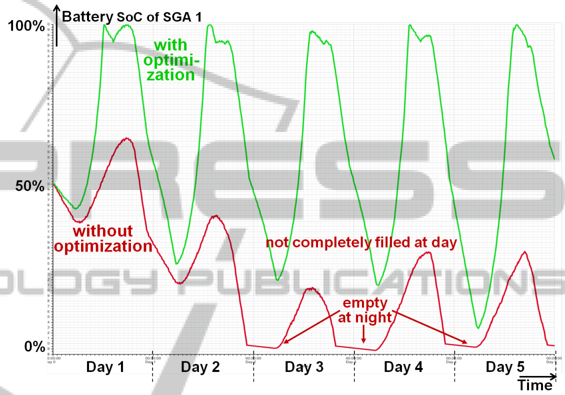


Figure 10: Comparison of Battery Status with and without Optimization.

This example proves that the two-level control architecture is very reliable. The SGD optimization can balance the demand and supply even under extreme situations. Nevertheless, this situation should be avoided in the praxis, since power transmission among SGAs will cause power loss. The guideline for SoftGrid is to generate and consume power locally. Power transmission among SGAs is for mutual support only. With the help of our simulation system, system design flaws like the above example can be detected in the early stage.

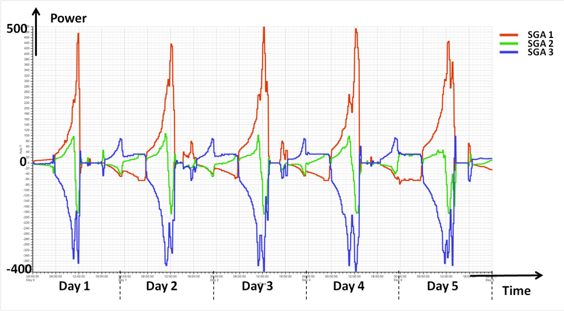


Figure 11: Power Transmission among SGAs.

6 CONCLUSIONS AND FUTURE WORK

In this paper, the concept of SoftGrid as a green field approach for smart grid is presented. It is a power flow optimization and optimal scheduling based decentralized power system, which adopts the two-level control architecture. This two-level control architecture can build up a local grid from scratch and integrate the local grid to any existing power grid. The concept of SoftGrid is verified through system modeling and simulation. The flexible simulation software allows user to design systems with different network topology and test system designs under different scenarios. The simulation results show that SoftGrid combines the advantages of smart grid and microgrid, providing a power grid solution with both flexibility and reliability. It stands for the power grid development trend in the future. The optimization models in SGA and SGD can be adapted to meet different user needs. In general, the SGA optimization is a MILP Problem solved by the CBC solver and the SGD optimization is a NLP problem solved by the Ipopt solver. This separation avoids the difficulty of solving a MINLP problem and thus allow the problems to be solved on an embedded computer. The details of optimization models will be explained in future publications. The hardware realization of this concept is now under test.

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