HOLARCHY THEORY FOR SMALL-SIZED POWER GRIDS

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ABSTRACT

Renewable energy sources are gaining more and more favor for ecological, economical reasons. Wide implementation of plants on such sources leads to an increase of uncertainty level in power grid on supplying part as most of them are straightly connected to weather conditions. While power loads are usually complex values with random trend characteristics too. Especially it concerns small-sized power grids where power load curves are even more unpredictable. One of the solutions is to implement smart grid techniques to balance the system and even to impact on customers' behavior. But it asks for a separate control design for every power complex. The offered in the article Holarchy theory leads to simplification in control design for power grids. Holonic structure asks for the same mathematical description for lower level elements and the full complex. It provides the possibility to formulate and then use in design only one optimization problem. While the practical task will be just to insert parameters of exact power equipment. The article is devoted to the formulation of such optimization problem for small-sized power grid and description of power complex as a Holarchy with all its' possible compounds.

Keywords: *power grid, smart grid, power control, renewable energy sources, Holon*

INTRODUCTION

Control other big power systems was automatized for a long time. Consequently, the first attempts for implementation of smart techniques on power grid were provided for the level of big geographical areas and cities where mostly big power plants were used for supply. While nowadays supplying elements of the grid are becoming smaller as many private entities are starting to use their own power plants on renewable energy sources as described in [1]. Thereof a demand for small-sized power grid's control is emerging. And as users of small-sized power grids will not provide manual control, the smart power grid is necessary.

There are several approaches for power grid's control. Brief description can be found in [2]. The approach with biggest potential is decentralization as it leads to increase in the effect of others too because it engages end customers into the grid's control [3]. Also, it can be fully automated and become a smart grid.

To be used in a smart grid control algorithm should be designed as in [4]. For any power grid, such design should be done for every exact case. Whereas the cost of proper control system design hasn't considerably changed. In case of big power grids such cost is affordable. While for small-sized power grids economically ineffective to design it separately.

In first part of the article “Holarchy” theory as a base for power grid’s decentralization is described. It is a proper instrument for the previously described task as it gives the possibility to formulate only one optimization problem and simplify the control design process. While the second part consists of example of “Holarchy” theory application on a small-sized power grid. The third part is devoted to the formulation of exact mathematical description for a small-sized power grid. As a result, an optimization problem is provided in the fourth part. In the fifth part the control system of power grid is described. At the end conclusions and perspectives are introduced.

HOLARCHY THEORY

Holarchy theory was firstly implemented in manufacturing processes. It was used for the optimization of a full process by dividing it into subsystem of special forms as reviewed in [5]. Then each part was optimized considering a main optimization task of the process. In the article it is offered to implement the theory to power grids.

The contrast of the Holarchy theory to the classical “system-subsystem” approach is that Holon is the whole and the part at the same time as described in [6]. Consequently, mathematical models and optimization problems for every Holon or Holarchy are universal.

The first step in applying the Holarchy theory is to formulate basic elements or Holons of a Holarchy which are both at the lowest and highest levels. For a power grid Holons from any level of Holarchy can be classified in three types: pure consumers, pure suppliers and mixed types as in figure 1.

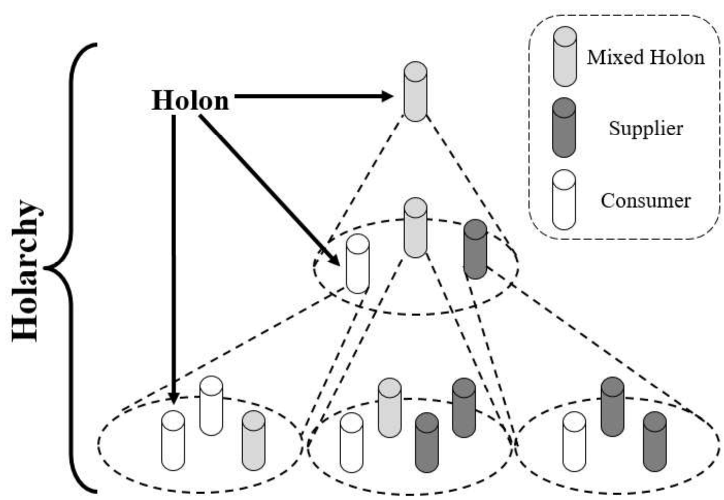

Figure 1. Holarchy and Holon principle

Pure consumer can only take power from the system, pure supplier only provides power to the system, while mixed type Holon at some point can be a supplier of energy, and at other time consumes energy. Examples for that types are: an electric power vehicle as a consumer, a wind plant as a supplier and a battery storage as a mixed type. While Holons of higher level can be combined by Holon's type at lower level, by a placing or an electric connection within a grid. More logical to connect Holons by a placing principle and then make even lower level by separating plant by their technical characteristics.

For example, a small building's power grid as a Holon should be divided by elements type. There Holarchy on the middle level will consist of two supplying Holons, one consuming Holon and one mixed Holons – wind turbine, complex of solar plants, complex of all consuming devices and complex of power accumulators consequently.

While small area's power grid with several buildings with own grid should be divided by placing principle. There every building will be a mixed Holon of middle level, while power plants used within their power grid will be their Holons of lower level. At the same time big plants that are supplying or consuming energy not to or from inner building's power grid also become Holons of middle level.

Anyway, Holons from the highest or lowest level can be classified into discussed types: supplier, consumer or mixed. While Holons on the highest level mostly will be of mixed nature.

EXAMPLE OF THE HOLON SYSTEM FOR SMALL-SIZED POWER GRID

Holonic approach can be implemented in design of smart grid control for small-sized entity as shown on figure 2.

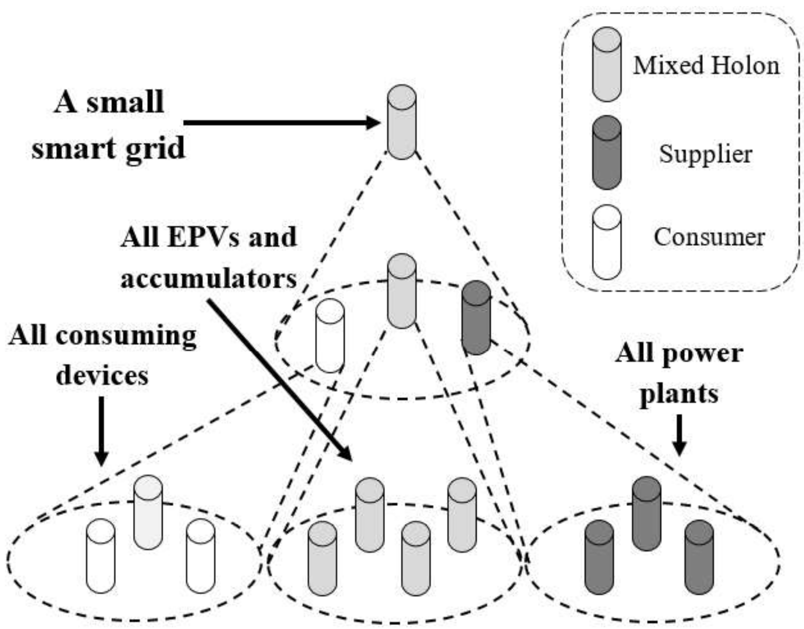

Figure 2. Small sized power grid as a Holon

As such small-sized power grid a building or an estate with a complex power system can be considered. The only requirement is to have complexity in its power system's structure: power plants as local suppliers and/or some kind of power storage.

For small-sized Holarchy controlled Holons of a lower level usually have its exact features, so, can be fully mathematically described. Then for middle level power plants are combined in one or several Holons. If there are plants that work on different RES, they are recommended to connect within different Holons. The same works for consumers. For example, residential consumption that is most uncertain should be divided from administrative power load into several Holons. Also, in some power grids consumption can be separated into mandatory and supplementary Holons. Especially it is actual for autonomous power grid with no connection to central grid.

Also the Holons should be analysed for possibility to be controlled. Mainly controlled Holons are power storages, but in some systems power plants or even consumers can be controlled too. For example, in autonomous power grids supplementary consumption or some power plants such are fuel generator or hydro-power plant can be partly or fully controlled.

MATHEMATICAL MODEL OF POWER GRID AS A HOLON

A small-sized power grid in its extended version consists of power loads, a set of power plants (solar panels, wind, etc.), battery storage and a connection to a central grid.

Power loads' impact on a grid is uncertain static and dynamic parameters. In the research will be utilized only static parameter – active power (*P*) – as it is used for regimes and control calculations. The parameter depends on voltage and frequency (*Vs* and *fs*) of a power supply and changes within the minimum and maximum limits that can be calculated if loads are known. While in some systems even that limits can be variable because of partly unknown loads. To minimize the uncertainty of power loads forecasting can be used. Such forecasting can be provided by classical regression methods or more advanced intellectual methods as shown in [7].

The power plants impact on a grid can be calculated much easier. Solar panels' output can be calculated as:

$$P_{SP} = P_{STC} \frac{G(\beta, \alpha)}{G_{STC}} \left[1 + \gamma(T_C - T_{STC})\right],$$

where P_{STC}- solar panels output under standard conditions, $G(\beta,\alpha)$ - incident irradiance on the plane of the panels (W/m^2), G_{STC}- incident irradiance under standard conditions (W/m^2), γ - power temperature coefficient, T_{STC} - temperature under standard conditions (^{0}C), T_C- cell temperature (^{0}C).

$$T_C = T_a + \frac{G(\beta, \alpha)}{800} \cdot (T_n - 20),$$

where T_a - ambient temperature (^{0}C), T_n- temperature of nominal cell operation (^{0}C).

While P_{STC}, γ, T_n is nominal values provided by manufacturers for any solar panel. [8]

Wind plants' performance can be formulated as:

$$P_{WT} = 1/2 \cdot \rho \cdot A \cdot C_p \cdot v_{(Z)}^3,$$

where ρ - air density (kg/m3), $v_{(Z)}$-wind speed at the wind turbine's height (m/s), A - working area of wind wheel (m2), C_p- wind plants' power coefficient. While A and C_p is provided by manufacturer. [8]

Anyway, power supply of most of the plants on RES straightly depends on weather conditions that are uncontrollable.

Battery storage is used as a buffer between power loads and supply from RES. Its' main parameters for smart grid are a state of charge (SoC) and nominal power capacity and voltage.

Previously described "Holarchy" principle can be applied for a small-sized power grid with a connection to a central grid. Then the power grid is high level Holon, it's loads, supplying power plants and battery storages are lower Holons, while central grid is higher level Holon. Whereas power impact on the higher Holon will have positive value if it supplies energy and negative value if it consumes.

For implementation to a controller or other computing facility it is strongly recommended that all similar loads and power plants would be incorporated in several inner Holons. P_l is total consumption, P_s is total inner supply, P_b is input (positive value) or output (negative value) from battery storage.

Total power impact (P_t) on central grid at any point can be calculated from the sum:

$$P_t = \sum_{i=1}^{n} P_{hi} \tag{1}$$

Where P_{hi} is every inner Holon's power, n is number of all inner Holons.

OPTIMIZATION PROBLEM FOR THE HOLON

As a factual matter small-sized grids without power storage could be optimized just by minimization of sum (1) online:

$$P_t \rightarrow min. \tag{2}$$

On a hardware side of control process, it is to switch on or off supplying plants and central grid.

But with incorporation of power storage optimization problem become more complex, as it can be used to buffer energy to increase inner efficiency of power supply. Consequently, it smooths consumption and supply curve from and to the central grid.

For the foregoing reasons the optimization problem for a smart grid can be formulated as minimization of required power within m hours' period with an inequality constraint:

$$\sum_{j=1}^{m} P_{tj} \rightarrow min, \quad (3)$$

$$SoC_{min} < SoC_j < SoC_{max},$$

Where SoC_j is battery's state of charge at j-hour.

m should calculated as a period of time when fully charged battery storage can cover some mandatory consumption without additional supply. While SoC_{min} and SoC_{max} are operational parameters of exact accumulators for the best utilization. For electric batteries these parameters depend on materials, operating environment, etc. Whereas for other types of accumulator (for example, water storage tank) that limits can extend till 0% and 100%.

Beside that dynamic power costs are used worldwide to smooth a power consumption trend, while in Kazakhstan's power grid it is not implemented. But, if such approach for power management will be applied, the optimization problem can be modified to minimize not just consuming power, but exact cost of it:

$$f_j(P_t) \rightarrow min \quad (4)$$

Where $f_j(P_t)$ is power cost's function from power level at exact hour j.

CONTROL SYSTEM FOR SMART GRID

Basic control system for smart grid is shown in figure 3.

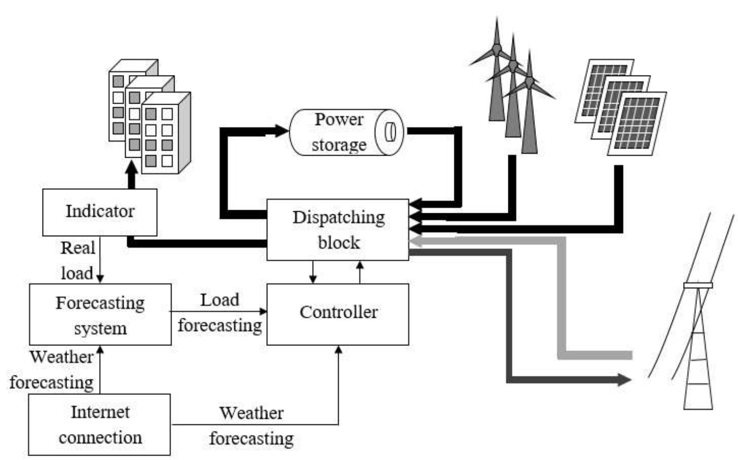

Figure 3. Small sized power grid as a Holon

As a power grid's Holons power consumption, wind turbines' complex, solar plants' complex, power storage is considered. Also connection to central grid for both possible supply and consumption is featured. In figure 3 can be seen that small-sized smart grid consists of five blocks: a controller, a dispatching block, indicators, some kind of forecasting system and an internet connection to upload a weather forecasting.

The controller beside real parameters from power grid received by indicators and the dispatching block uses load and weather forecasting. Weather data is used for calculation of future power supply from RES plants. It allows to utilize optimal control algorithm based on previously stated optimization task. After data processing the controller send the control input to the dispatching block that switches controlled parameters to match the optimal control.

While forecasting system processes real power loads from indicators and weather forecasting from external sources by the internet connection.

The forecasting of power load for the super small sized power grids is unnecessary as it can be straightly calculated or even controlled. But for power grids with more than one consumer the load is hardly predictable, so forecasting is obligatory as stated in [9]. The brief description of possible forecasting methods can be found in [10].

Such control system can be implemented both on newly combined hardware or on existing complexes for smart grid as in [11].

CONCLUSION

With wide adoption of renewable energy sources in small-sized private power grids the necessity of smart control technologies for such grids grew tremendously. Such necessity firstly based on impossibility of private users to dispatch and provide power balance manually. While with unstandardized structure and elements of such grids the control design has to be provided for every exact system. The first part of such design is to formulate mathematical description of the system to calculate then exact optimal controlling algorithm. Only then it can be implemented into a controller. So, the cost of such design is economically inadequate to the total cost of a private grid.

The implementation of Holarchy theory with its possibility to describe both system and subsystems by one mathematical model provides possibility to design one controlling algorithm and then to scale it further. This approach sensibly decreases an end cost of a control design. Considered in the article small-sized power grid consists of several types of power plants, power loads and power storages. Implementation of Holarchy theory on the small-sized power grid is described.

In the next part mathematical description of every element is provided. The main parameters of power loads are stated. The dependencies of power plants' output on weather conditions are formulated. Then the total power of the grid is calculated.

The main result is the optimal problem for the control algorithm that is formulated next. First optimal problem is designed for the system without any power storage and can be used for online control. While next optimal problem is more complex as it is provided for a grid with power storage. As such grid has several dispatching scenarios the control should be planed for some period of time. Also operational limits on state of charge for power storage should be considered as a condition for the optimization problem. Then the optimization task for the dynamical power costs are stated.

At the end functional scheme of a smart grid on Holarchy base is fully described. Also connection to the central grid for both import and export of electric power is considered.

In perspective such approach can be applied for power grids of bigger size. Even on a region or country level. While power load forecasting methods for a central grid should be researched more as the small sized power grids become not just a consuming but also supplying sub-systems. Also more detailed formulation of an optimal problem based on dynamical cost can be done.

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