Energy Transfers Diagrams for Renewable Energy Systems

Witold Marańda

***Abstract*—Local systems, composed of Renewable Energy Sources, generators, loads and storage devices, perform energy transfers between system components. The number of possible configurations of energy transfers grows rapidly with the number of system components, making reliable energy management a difficult task.**

This paper presents an approach to describe the system operation, according its energy transfers, in form of the automatically generated directed graph. The approach is focused on finding the complete set of all possible system states, that are not prohibited by the operation strategy nor inconsistent.

The method is very general and can be applicable to arbitrary system configuration, that can be described at the level of components with only basic attributes and sequences of interactions. Namely, the system components are categorized according to their roles (source/sink/both), fitting in the system (rigid/adaptive) and their persistence (permanent/temporary).

The key point of this method is that the final energy transfers diagram is extracted from the initial full graph by filtering out the nodes and transitions not allowed by the defined system operation principle, but leaving all the remaining states. In this way, no consistent system state is overlooked.

The generated diagram may be used for studying and visualizing system operation policy, registering the energy flows, discovering doubtful states and transitions or finally for implementation of a reliable energy management controller.

***Index Terms*—renewable energy system, energy transfers diagram, energy management, energy storage, photovoltaics.**

I. INTRODUCTION

INTEGRATION of Renewable Energy Sources (RES) into electric grids is becoming very popular for small scale applications, implementing the concept of distributed energy generation and management. This is mainly due to easy access to photovoltaic or wind generators and efficient storage solutions with Li–ion or supercapacitors technology available at relatively low-cost [1]. Moreover, the rising popularity of electric vehicles creates an opportunity for more rational utilization of RES and integrating car battery in a local energy system as smart storage device [2].

RES energy systems, involving RES-generators, grid-coupling, loads and storage devices, perform energy transfers between system components. The number of possible configurations of energy transfers grows rapidly with the number of system components, making reliable energy management a difficult task.

II. BACKGROUND

The concept of distributed energy generation, involving interaction between electrical network maintainers and small but numerous RES systems, may totally change the electric network architecture [3]. This also implies that the distributed systems will have to share the responsibility for reliable grid operation with electric network operator. The future RES systems will have to be more network-aware and cooperative by using smart energy management [4].

The control of RES-systems is performed according to the adopted principle of operation, where actions are taken in predefined sequences and some situations are prohibited. For example, the interaction with the utility grid may be implemented according to various scenarios (e.g. minimal purchase, maximal feed-in, equal balance or optimal buy/sell ratio) [5]. Another example is the strategy for utilization of local storage and its impact on grid (e.g. maximal autonomy, multi-stage storage, optimal grid interaction) [6].

The complete energy flows diagram graphically visualizes all system states and its transitions. This allows for identification of non-obvious or critical situations and registering all the energy transfers in a system. It may also greatly help to study the system operation principle and verify the correctness of implemented rules. The validated diagram is then the starting point to the design of system controller capable of handling all possible states of operation [7].

In contrast to existing solutions, which are often dedicated to particular system configurations and deal with the implementation details, this work focuses on making a description of arbitrary system at abstract level of energy flows between components. This paper presents an approach to making the complete energy transfer diagrams for arbitrary system composed of RES generators, utility-grid connections and a number of various loads and energy storage devices.

The key point of this method is that the final energy transfers diagram is extracted from the initial full graph by filtering out the nodes and transitions not allowed by the defined system operation principle, but leaving all the remaining states. In this way, no consistent system state is overlooked.

Since the method deals with system components at abstract level, it is very general and therefore applicable to arbitrary system configuration that can be defined with only few general features.

In brief, the method requires that the system components are first categorized according to their three aspects:

- roles in the system: source, sink, both
- fitting in the system: rigid, adaptive
- persistence: permanent, temporary.

The initial diagram is huge since it embraces all the possible valid states and transitions. Then, the designer can apply rules to limit the number of allowed system states (nodes).

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Subsequently, the principle of system operation must be taken in account by applying rules to transitions to be filtered out.

Finally, the designer is left with the energy transfer diagram, that is guaranteed to contain all the states and transitions that have not been ruled out either by the system definition or by principle of operations.

The author is using own custom-software, but the method can be implemented with any suitable programming environment.

III. MOTIVATION

Making a complete energy transfer diagram for the adopted management strategy in a RES-system composed of just few elements is relatively easy.

Let us consider Fig. 1, which represents an example of grid-coupled (G) PV-system (P) with local load (L) and storage (S), operating with principle to minimize the energy purchase from grid. Both PV and load have variable in time operating power, but the local consumption is never at zero and the storage has no charge/discharge power-rate limitation.

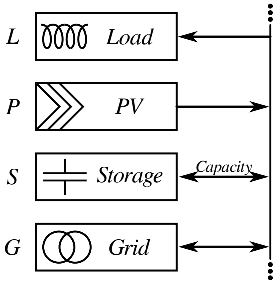

Figure 1. Simple system with Grid, PV, Storage and Load

The nodes of this system diagram (Fig. 2) are the active sources and sinks involved in the currently ongoing energy transfer. The state description puts the sources at the left and sinks at the right side of the central arrow.

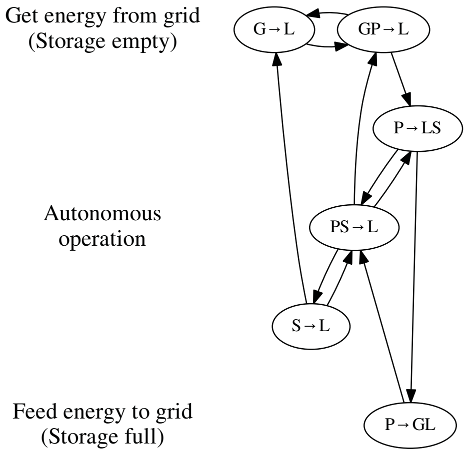

Figure 2. Diagram for G-P-S-L system

For example, GP→L means the load is supplied from PV with grid support, whereas P→LS represents the situation when PV satisfies the load and feeds the excess of energy to the local storage device.

The transitions between states corresponds to the possible and allowed changes in the source-to-sink configuration. Essentially, the transitions reflect the system operating policy.

The important assumption for making the graph is that any transition is triggered by change of only one component, that may become active, inactive, change its source/sink role or being replaced by other of the same kind. This is justified because the functioning of separate components is not correlated in time, e.g. PV vs. load, load vs. storage, storage vs. PV and etc.

However, when the system complexity grows, identifying all possible energy flows in the diagram is not so obvious and the uncertainty arises about its completeness. The system in Fig. 3, which is identical to Fig. 3 (the same components and operation principle) with only one exception: the storage is a battery with charge/discharge limit.

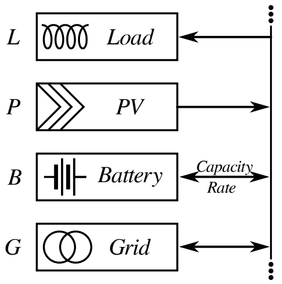

Figure 3. System with Grid, PV, Battery and Load

The energy flow diagram (Fig. 4) for the new system is already substantially more complex: it has 3 additional nodes and 14 new transitions.

The comparison of Fig. 2 and 4 demonstrates that for a more complex systems, making the diagram by hand would a big challenge. Therefore, a formal approach to the diagram generation is needed.

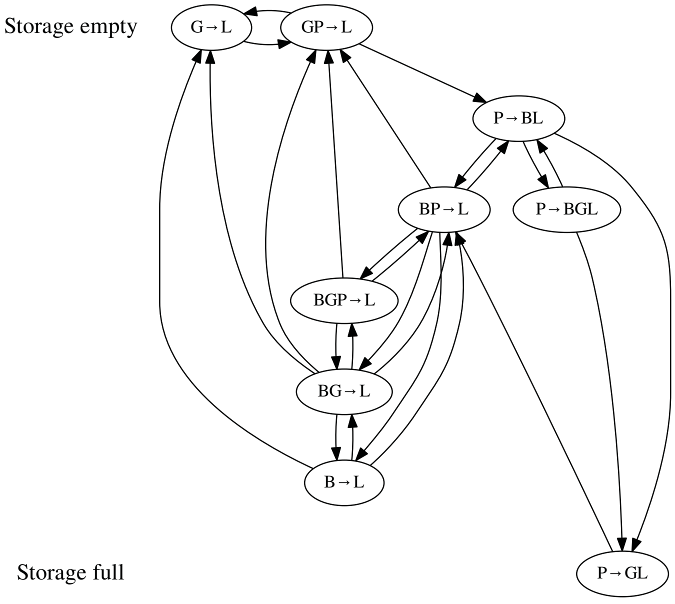

Figure 4. Diagram for G-P-B-L system

IV. DIAGRAM GENERATION

A. Components

The method of automatic generation of energy flow diagrams requires that all RES–system components must be categorized into according abstract, generic features, using the nomenclature from Fig. 5 developed in this paper:

- role (source, sink, both) — the ability to generate or consume energy; the component can be ”both” (”sink” and ”source”, e.g. battery), but never at the same time.
- fitting (rigid, adaptive) — reflects the ability of adjusting the power delivery or consumption; loads are typically ”rigid” (power demand must be satisfied), whereas storage is commonly ”adaptive”; the PV-generator is treated here as ”rigid” due to requirement of MPP-operation, whereas grid is always ”adaptive”.
- persistance (temporary, permanent) — reflects the component activity in energy exchange; the ”permanent” load would be always sinking power, PV and storage are ”temporary” due their nature, whereas grid with no capacity limitations is ”permanent” (but may be disconnected if not needed, since it is ”adaptive”).

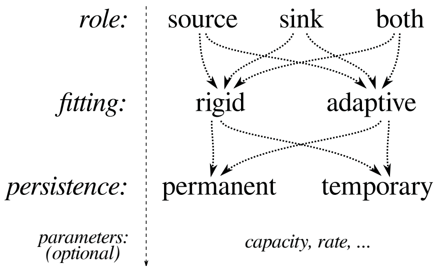

Figure 5. System component nomenclature

B. States

At any time, the RES-system is in one of its allowed states (graph nodes), defining its energy flow from sources to sinks.

Let us consider the arbitrary and totally unrestricted RES-system. All its components may play the role ”both”, but may have only single fitting and single persistence, yielding 4 generic types of components as in Table I. There may be several components of the same kind, but here they are all treated here as a single one representative for its kind.

TABLE I
UNRESTRICTED SYSTEM DEFINITION

Name	Symbol	Role	Fitting	Persistence
Adaptive-Permanent	Ap	both	adaptive	temporary
Adaptive-Temporary	At	both	adaptive	permanent
Rigid-Permanent	Rp	both	rigid	permanent
Rigid-Temporary	Rt	both	rigid	temporary

Since the system operation is unrestricted (no policy), the number of all possible states is 256 (all combinations of sources and sinks, including empty), but some nodes must be excluded as invalid (namely any ”rigid”→”rigid” states), which finally gives a graph with 223 possible operation states (some of them may seem exotic, but conceivable).

Such graph — to big to be shown here in details — represents a pool containing all possible RES-systems with all operating policies.

C. Transitions

The adopted mechanism of making a transition between states is based on single-event triggering, that may happen to any component, e.g. battery becomes empty/full, PV-generator is switched on/off, load consumption rises/drops, etc.. Since the events are assumed to be not correlated in time, the transitions are between states with just one component difference.

For each state, all events for all components (except ”Rigid-Permanent”) are considered as capable of making a separate valid transition, as follows:

- a component may be added or removed (switched on/off)
- a component may be replaced by a component with the same role
- a component may be replaced by a component with the opposite role

The transitions leading to invalid nodes or conflicting with component properties are eliminated from the graph. The remaining transitions correspond to conceivable real-life events.

D. Rules

The energy flow diagram for a given system can be extracted from the complete unrestricted graph by applying rules to nodes and transitions. The node-rules express the system architecture (configuration of components) and the transition-rules describe operating principle (sequence of actions).

The node-rules are either inclusive or exclusive and may be applied to individual components or to any ”src-sink” pairs, as follows

- `node, exclude|include, src|sink, src|sink, component-A, component-B`
- `node, exclude|include, all|only, src|sink, component`

The transition-rules are stated similarly, but they refer to allowed/disallowed sequences of events, as follows:

- `tran, exclude|include, src|sink, src|sink, component-A, component-B`
- `tran, exclude|include, src|sink, component`

E. Procedure

The diagram making procedure is composed of the following steps:

- Identification of separate system components.
  The loads may be treated separately or as a single item, depending on their significance; the same applies to generators or storage devices.
- Categorization of system components in terms of roles, fitting and persistence.
  Each component must have a 3-parameter description and there may be several separate components if the same kind if needed.
- Writing the node and transition rules.
  Rules are expressed with statements specifying what states are allowed (system configuration) and which transitions (operation policy) are allowed or prohibited.
- Run diagram generating software.
  Program reads the system description (components and rule), makes the initial full graph (according to the components) and reduces it (according to the rules).

F. Examples

The procedure to make energy transfer diagrams may be best explained by two examples, referring to the simplest and the most general, unrestricted case of a system.

The simplest, non-trivial energy system is composed of only two elements: electric grid (**`G`**) and load (**`L`**). When the elements are defined as ”both, adaptive, permanent” for **`G`** and ”sink, rigid, temporary” for **`L`**, the allowed states for the system are shown in Fig. 6.

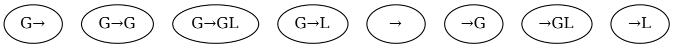

Figure 6. All states for the simples system L+G

Invalid states (”rigid”→”rigid”: →GL, →L) are eliminated as conflicting with definition of ”rigid” elements, with empty source or sink treated as rigid. Two other states involving G→G transfer, (not possible if G is one element) has to be eliminated by the single rule:

- `node, exclude, src, sink, G, G`

Without any other rules, the system can function in four different states and undergo the transitions according to the diagram in Fig. 7

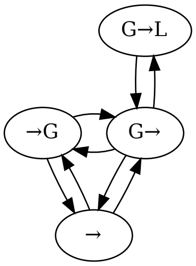

Figure 7. Diagram for L+G system with L being ”temporary, rigid, sink”

However, when description of load L is changed to ”permanent”, the graph is automatically reduced the only allowed states with no transitions, as shown in Fig. 8

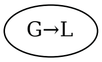

Figure 8. Diagram for L+G system with L being ”permanent, rigid, sink”

The second example represents the opposite case of complexity. The unrestricted 223-node graph defined by Table I can be made smaller by prohibiting to have the same kind of components as source and sink at the same time (e.g. one battery to another battery, one grid to another grid, etc) by the following rules:

- `node, exclude, src, sink, Rp, Rp`
- `node, exclude, src, sink, Rt, Rt`
- `node, exclude, src, sink, Ap, Ap`
- `node, exclude, src, sink, At, At`

The resulting graph (shown in Fig. 9) has only 55-nodes and is composed of 3 disjoined parts due to the presence/absence of ”Rigid-Permanent” component.

For the systems from Fig. 3 the definition is given in Table II.

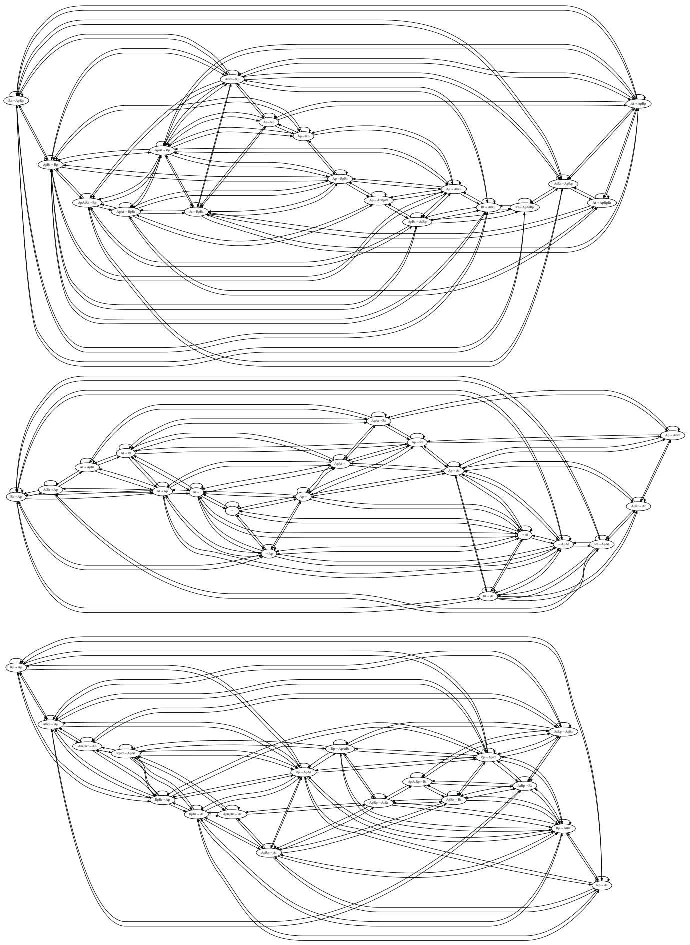

Figure 9. 55-node diagram with weak restrictions

TABLE II
SYSTEM DEFINITION FOR FIG. 3

Name	Symbol	Role	Fitting	Persistence	Parameters
PV-array	P	source	rigid	temporary	
Load	L	sink	rigid	permanent	
Battery	B	both	adaptive	temporary	capacity, rate
Grid	G	both	adaptive	permanent	

Its flow diagram (Fig. 4) was made automatically according to the rules:

- exclude same components as ”src-sink”:
  `node, exclude, src, sink, G, G`
  `node, exclude, src, sink, B, B`
- consider only the nodes containing load as sink
  `node, include, only, sink, L`
- never charge battery from grid or the opposite:
  `node, exclude, src, sink, G, B`
  `node, exclude, src, sink, B, G`
- grid-only operation prohibits discharging (charging) battery as next:
  `tran, exclude, src, G, B`
  `tran, exclude, sink, G, B`
- discharging (charging) battery prohibits using grid-only as next:
  `tran, exclude, src, sink, B, G`
  `tran, exclude, sink, src, B, G`
- battery prohibits switching directly the grid role:
  `tran, exclude, src, sink, G, G`
  `tran, exclude, sink, src, G, G`

V. CASE-STUDY

Let us consider a RES-system (Fig.10) with PV and grid, containing in addition 2–stage local storage system:

- large-capacity: storage with charge/discharge rate limitations (e.g. chemical battery),
- small-capacity: storage without rate limitation (e.g. supercapacitor).

The supercapacitor protects the battery against frequent and shallow charge/discharge cycles that are created by the PV-generator [8].

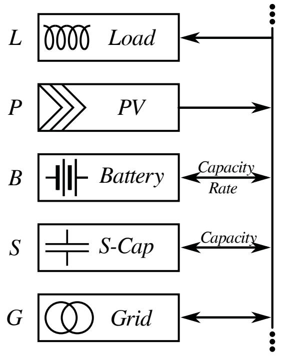

Figure 10. System with 2–stage storage

According to the introduced nomenclature, the system can be categorized as in Table III. The node and transition rules can be best explained with the comments on their functionality.

TABLE III
SYSTEM DEFINITION WITH 2–STAGE LOCAL STORAGE

Name	Symbol	Role	Fitting	Persistence	Parameters
PV-array	P	source	rigid	temporary	
Load	L	sink	rigid	permanent	
Battery	B	both	adaptive	temporary	capacity, rate
Super-Cap.	S	both	adaptive	temporary	capacity
Grid	G	both	adaptive	permanent	

The supercapacitor (component S) with no rate limitation can be characterized by the following rules:

- grid support is not needed for discharge/charge:
  ```
  node, exclude, src, src, S, G
  node, exclude, sink, sink, S, G
  ```

The principle of system operation and the corresponding rules can be described as follows:

- storage is only for local consumption:
  ```
  node, exclude, src, sink, B, G
  node, exclude, src, sink, S, G
  ```
- charging is allowed from PV only:
  ```
  node, exclude, src, sink, G, B
  node, exclude, src, sink, S, B
  node, exclude, src, sink, G, S
  node, exclude, src, sink, B, S
  ```
- charging has priority over feeding the grid:
  ```
  tran, exclude, src, sink, B, G
  tran, exclude, src, sink, S, G
  ```
- local consumption is always present:
  ```
  node, include, only, sink, L
  ```

The 2–stage storage requires special attention, since the two storages and grid must me used in strict order, defined by the rules:

- storages are charged/discharged separately:
  ```
  node, exclude, sink, sink, S, B
  node, exclude, src, src, S, B
  ```
- charge/discharge order must be maintained:
  ```
  tran, exclude, src, sink, G, B
  tran, exclude, src, sink, S, B
  tran, exclude, src, sink, B, B

  tran, exclude, sink, src, G, B
  tran, exclude, sink, src, S, B
  tran, exclude, sink, src, B, B

  tran, exclude, sink, src, S, G
  tran, exclude, sink, src, B, G
  ```
- direct grid switching is not allowed:
  ```
  tran, exclude, src, sink, G, G
  tran, exclude, sink, src, G, G
  ```
- sourcing(feeding) the grid implies empty(full) storages:
  ```
  tran, exclude, src, G, B
  tran, exclude, src, G, S
  tran, exclude, sink, G, B
  tran, exclude, sink, G, S
  ```
- discharging(charging) the battery implies empty(full) supercap:
  ```
  tran, exclude, src, B, S
  tran, exclude, sink, B, S
  ```

The final, automatically generated diagram for the system is show in Fig. 11. The graph is composed of 12 states, but the 2–stage local storage introduces the complexity. It is clearly visible, that system may oscillate” in some closed path and never reach certain states.

Next, it is up to the system designer to identify the actual conditions for the transitions, but it is guaranteed that no possible event was omitted in the diagram.

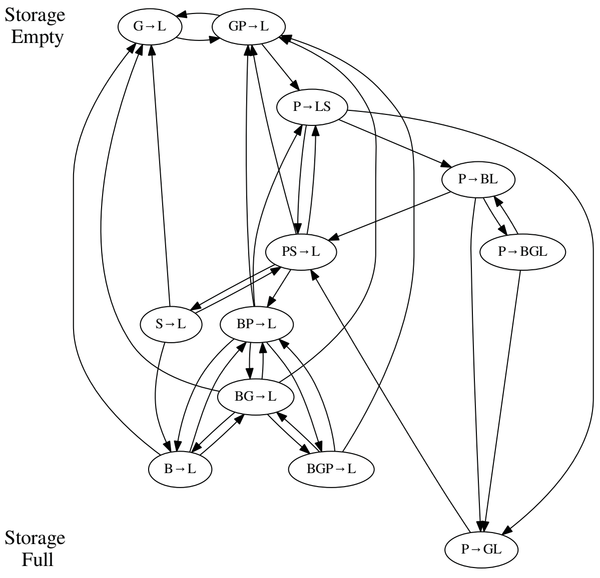

Figure 11. Diagram for G-P-B-S-L system

VI. CONCLUSIONS

Complexity of energy management in RES-systems grows rapidly with the number of components and custom operation principles.

The system operation may be described at abstract level with a directed graph of energy transfers. At any time moment, energy is being transfered between some elements, (system state) and the transfer configuration may change to another (system transition).

Even simplest systems, with only a few components, offer many possible energy management scenarios. For more complex systems, discovering all possible transitions in the energy flow diagram becomes a challenge. On the other hand, reliability and safety of the RES-system may depend on identification of complete list of allowed system states and possible transitions.

This paper presents an approach to automatically making the complete energy transfer diagrams for arbitrary system configuration by extracting the valid nodes and transitions from the initial full graph, according to the defined rules, by filtering out the nodes and transitions not allowed by the defined system operation principle, but leaving all the remaining states. In this way, no consistent system state is overlooked. This work is an overview of the effort still in progress.

The generated diagram may be used for studying and visualizing system operation policy, registering the energy flows, discovering doubtful states and transitions or finally for implementation of a reliable energy management controller.

It was demonstrated by the realistic non-trivial example of grid-coupled RES-system composed of PV-generator, local load and 2–stage storage, that the method is capable for automatic generation of the complete flow diagram for the RES-system. Similarly, the diagrams can be made for systems with other operation principles.

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