Abstract

The paper will discuss the possibility of using Finite State Machines (FSM) for modeling the operation of distribution power system. The paper will point out basic characteristics describing an operation of nowadays distribution grids, which are intended to be operated as smart grids in the future. This change requests a new approach to distribution system modeling that enables to study the network operation from different points of view. There are many ways how to do it. One of them could be the application of FSM. The paper will be focused on the basic justification of FSM usability for distribution system modeling.

1. Introduction

The way of power distribution network’s operation has been changed. Nowadays more and more energy flows through networks, which are mostly older than forty years. Moreover, renewable energy sources and smaller generation units start to play significant role in power distribution networks operation, despite of the fact that they have to cope with big infrastructure problems. These sources change typical direction of power flow as well as a typical shape of daily load diagram. Their generation is unpredictable in most cases, what results in unforeseen power peaks transmission causing plumbless losses.

Power distribution networks were not designed to meet these new requirements. To do so, their infrastructure has to be changed or improved. One way how to do it is an application of intelligent devices, which are able to make use of benefits provided by information and communication technology (ICT). This approach is presented and known as Smart Grid. One of declared Smart Grid benefits is the upgrade of distribution networks operation from classical “energy transport channels” to “intelligent networks”. Network’s intelligent should be provide by an automated energy management system regulating loads’ energy demands, an energy storage and the supply of actually produced energy in distributed generation to the grid.

First project trying to achieve Smart Grid functionality, partially of fully, can already be found in Italy, Sweden or Denmark. There is also a pilot project introduced by the energy company ČEZ in the region Vrchlabí in Czech Republic. The results of these projects will give us an idea how it could look in the future.

2. Smart Grid concept

In June of 2008, the U.S. Department of Energy held a meeting of industry leaders who identified seven defining traits of what a Smart Grid will do [1]:

1. Optimize asset utilization and operating efficiency.
2. Accommodate all generation and storage options.
3. Provide power quality for the range of needs in a digital economy.
4. Anticipate and respond to system disturbances in a self-healing manner.
5. Operate resiliently against physical and cyber attacks and natural disasters.
6. Enable active participation by consumers.
7. Enable new products, services, and markets.

What is not explicitly stated here, but is equally important, is that a fully developed smart grid concept goes far beyond smart meters! It includes technologies at both the transmission and distribution level and extends to both IT hardware and software, such as monitoring and control systems, as well as primary equipment like transformers and relays [2].

The table 1 provides a concise summary of some of the differences as they appear in various parts of [2]. The last item in the Tab. 1, generation topology, hints at what is perhaps the most fundamental shift that a fully realized smart grid will require. Today’s power systems are designed to support large generation plants that serve faraway consumers via a transmission and distribution system that is essentially one-way. But the grid of the future will necessarily be a two-way system where power
generated by a multitude of small, distributed sources—in addition to large plants—flows across a grid based on a network rather than a hierarchical structure. Just as the internet has driven media from a one-to-many paradigm to a many-to-many arrangement, so the smart grid too will enable a similar shift in the flow of electricity [2].

### Differences between current and smart grid

<table>
<thead>
<tr>
<th></th>
<th>Current Grid</th>
<th>Smart Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Communications</strong></td>
<td>None or one-way (typically not real-time)</td>
<td>Two-way (real-time)</td>
</tr>
<tr>
<td><strong>Customer interaction</strong></td>
<td>Limited</td>
<td>Extensive</td>
</tr>
<tr>
<td><strong>Metering</strong></td>
<td>Electromechanical</td>
<td>Digital (enabling real-time pricing and net metering)</td>
</tr>
<tr>
<td><strong>Power flow control</strong></td>
<td>Limited</td>
<td>Comprehensive (automated)</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Prone to failures and cascading outages (essentially reactive)</td>
<td>Automated, proactive protection (prevents outages before they start)</td>
</tr>
<tr>
<td><strong>Restoration following disturbance</strong></td>
<td>Manual</td>
<td>Self-healing</td>
</tr>
<tr>
<td><strong>System topology</strong></td>
<td>Radial (generally one-way power flow)</td>
<td>Network (multiple power flow pathways)</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Manual equipment checks, maintenance</td>
<td>Remote monitoring, predictive, time-based maintenance</td>
</tr>
<tr>
<td><strong>Generation</strong></td>
<td>Centralized</td>
<td>Centralized and distributed</td>
</tr>
</tbody>
</table>

Distributed generation (DG) is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators. In contrast to the use of a few large-scale generating stations located far from load centers—the approach used in the traditional electric power paradigm—DG systems employ numerous, but small plants and can provide power onsite with little reliance on the distribution and transmission grid. DG technologies yield power in capacities that range from a fraction of a kilowatt [kW] to about 100 megawatts [MW]. Utility-scale generation units generate power in capacities that often reach beyond 1 000 MW [3].

### 2. Finite State Machines approach

The operation of the network with applied smart grid concept requires more sophisticated and complex control, due to the application of both power and ICT technology. The building of required network’s infrastructure means huge investments for any distribution utility. Therefore it is very wise to model smart grid operation of distribution networks first, to identify necessary level of automation that will lead to planned functionality. Because the modeling of such network’s operation should be considered as the combination of models representing power devices, protection devices, communication devices, actuators and others, which responses varies in time, the simulation model would be very complicated. Moreover, some functions need to be modeled in simulation domains different from time domain. This approach will give us proper results on the one hand and it significantly simplified the modeling on the other. It is possible to combine a set of specialized simulation tools in co-simulation of course, but the other perspective way how to cope
with this modeling problem is the use of Finite State Machine that can be modeled e.g. in Ptolemy II software [4].

2.1 Finite State Machines

A Finite State Machine (FSM) is usually specified in the form of a transition table, much like the one shown in Tab. 2 [5].

<table>
<thead>
<tr>
<th>Current State</th>
<th>In</th>
<th>Out</th>
<th>Next State</th>
</tr>
</thead>
<tbody>
<tr>
<td>q₀</td>
<td>-</td>
<td>1</td>
<td>q₂</td>
</tr>
<tr>
<td>q₁</td>
<td>-</td>
<td>0</td>
<td>q₀</td>
</tr>
<tr>
<td>q₂</td>
<td>0</td>
<td>0</td>
<td>q₁</td>
</tr>
<tr>
<td>q₃</td>
<td>1</td>
<td>0</td>
<td>q₃</td>
</tr>
<tr>
<td>q₄</td>
<td>0</td>
<td>0</td>
<td>q₄</td>
</tr>
<tr>
<td>q₅</td>
<td>1</td>
<td>0</td>
<td>q₁</td>
</tr>
</tbody>
</table>

Tab. 2. Example of transition table for FSM

For each control state of the machine the table specifies a set of transition rules. There is one rule per row in the table, and usually more than one rule per state. The example table contains transition rules for control states named q₀, q₁, q₂, and q₃. Each transition rule has four parts, each part corresponding to one of the four columns in the table. The first two columns describe conditions that must be satisfied for the transition rule to be executable. They specify:

- The control state in which the machine must be.
- A condition on the “environment” of the machine, such as the value of an input signal.

The last two columns of the table define the effect of the application of a transition rule. They specify:

- How the “environment” of the machine is changed, e.g., how the value of an output signal changes.
- The new state that the machine reaches if the transition rule is applied.

In the traditional finite state machine model, the environment of the machine consists of two finite and disjoint sets of signals: input signals and output signals. Each signal has an arbitrary, but finite, range of possible values. The condition that must be satisfied for the transition rule to be executable is then phrased as a condition on the value of each input signal, and the effect of the transition can be a change of the values of the output signals. The machine in Tab. 2 illustrates that model. It has one input signal, named In, and one output signal, named Out. A dash in one of the first two columns is used as a shorthand to indicate a “don’t care” condition (that always evaluates to the Boolean value true). A transition rule, then, with a dash in the first column applies to all states of the machine, and a transition rule with a dash in the second column applies to all possible values of the input signal. Dashes in the last two columns can be used to indicate that the execution of a transition rule does not change the environment. A dash in the third column means that the output signal does not change, and similarly, a dash in the fourth column means that the control state remains unaffected.

In each particular state of the machine there can be zero or more transition rules that are executable. If no transition rule is executable, the machine is said to be in an end state. If precisely one transition rule is executable, the machine makes a deterministic move to a new control state. If more than one transition rule is executable a nondeterministic choice is made to select a transition rule. A nondeterministic choice in this context means that the selection criterion is undefined. Without further information either option is to be considered equally likely. Machines that can make such choices are called nondeterministic machines. Table 3 illustrates the concept. Two transition rules are defined for control state q₁. If the input signal is one, only the first rule is executable. If the input signal is zero, however, both rules will be executable and the machine will move either to state q₀ or to state q₃.

<table>
<thead>
<tr>
<th>Current State</th>
<th>In</th>
<th>Out</th>
<th>Next State</th>
</tr>
</thead>
<tbody>
<tr>
<td>q₁</td>
<td>-</td>
<td>0</td>
<td>q₀</td>
</tr>
<tr>
<td>q₃</td>
<td>0</td>
<td>0</td>
<td>q₁</td>
</tr>
</tbody>
</table>

Tab. 3. Non-Determinism

The behavior of the machine in Tab. 2 is more easily understood when represented graphically in the form of a state transition diagram, as shown in Fig. 3.

Fig. 3. State transition diagram.

The control states are represented by circles, and the transition rules are specified as directed edges. The edge labels are of the type c/e, where c specifies the transition condition (e.g., the required set of input values) and e the corresponding effect (e.g., a new assignment to the set of output values) [5].

2.2 Model example

The approach how to model power distribution network’s components by FSM can be shown on
following, very simplified, example. Let’s have a power transformer 110/22 kV, which is equipped with an automatic tap changer on its 110 kV side. Let’s say that we want to create its model, which calculates transformer phase current $i_T$ as an input for a model of overcurrent relay protecting the transformer. Transformer’s operation can be divided among a number of time periods, each taking a different time. Some of these periods can be described as steady-states that can be modeled by linear equations (it speeds up the simulation), the others as transients that have to be modeled by differential equations (it slows down the simulation). It’s very important to point out that states’ changing in time is stochastic.

To simplify this example we can assume that the protection relay is activated only if $di_T/dt$ is big enough. Taking this into account, we can say that a change of transformer current caused by a tap changer activity (controlled by AVR) can be taken as steady-state operation, represented by state $q_0$. On the other hand, a change of transformer current caused by a short circuit on transformers terminals can be taken as a transient operation, represented by state $q_1$.

A transition table of presented example is in Tab. 4. If a transformer’s tap is changed (n+ for up and n– for down), the transformer remains in steady-state operation and linear equations can be used to calculate a phase current. During a short circuit the transformer changes its state to transient and differential equations have to be used. When it’s over, the transformer returns to its steady state operation again. The graphical representation of Tab. 4 is shown on Fig. 4.

### Tab.4. Transition table for simplified example

<table>
<thead>
<tr>
<th>Current state</th>
<th>In</th>
<th>Out</th>
<th>Next state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>n+</td>
<td>linear eq.</td>
<td>$q_0$</td>
</tr>
<tr>
<td>$q_0$</td>
<td>n–</td>
<td>linear eq.</td>
<td>$q_0$</td>
</tr>
<tr>
<td>$q_0$</td>
<td>$di_T/dt &gt;$ threshold</td>
<td>differential eq.</td>
<td>$q_1$</td>
</tr>
<tr>
<td>$q_0$</td>
<td>$di_T/dt &lt;$ threshold</td>
<td>linear eq.</td>
<td>$q_0$</td>
</tr>
</tbody>
</table>

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### Bibliography


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