Multi-Agent Approach to Electrical Distribution Networks Control

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Abstract

A new approach to the configuration and operation of electrical distribution networks is proposed. Traditionally, the medium-voltage part of the electrical grid is operated in a centralised and static manner. In the context of electric sector deregulation and electric market liberalisation, the pertinence of this central organisation is no longer ensured.

This paper presents an alternative approach based on a multi-agent system, implementing a distributed control algorithm. Concepts used in communication networks have been applied and adapted to the electrical supply system.

1. Introduction

This last decade has been of great importance to the electricity supply sector. On one hand, many countries, especially in Europe, deregulated their national networks, privatised significant pans of it, and introduced market liberalisation in this industry. One the other hand, the whole energy sector is affected by world-wide CO2-reduction targets and more generally by environmental concerns. These fundamental changes put under question the conventional organisation of the electrical energy networks, at all levels: technical, operational, structural, commercial and even institutional.

In the traditional model, the electrical network sector is characterised by large vertically integrated entities occupying monopolistic positions over the whole supply chain (production – transport – transformation – distribution) and over large geographical regions. This is not only due to the important economies of scale achievable in the sector and the huge investments required, but also to geopolitical concerns. Still in the traditional approach, each step of the supply chain corresponds to a specific network layer (production and transport layer, bulk distribution layer or last-mile distribution layer). The energy flows unidirectionally through the layers from the top (production) to the bottom (consumption). Each layer is generally designed according a specific topology (respectively meshed, radial or point-to-point) and operated in a centralised manner.

This traditional model has been used for many years but complies difficulty with nowadays trends. In particular, the integration of small size power stations in the network is problematic. These dispersed generators, presenting a very high efficiency or a minimised environmental impact (e.g. wind mills), are conceived for on-site energy consumption and, therefore, cannot be directly connected to the production layer. Because of the stochastic character of some renewable energy sources and the potentially great number of distributed generation (DG) units inserted, a centralised operation of the intermediate layer (i.e. bulk distribution) is too complex. Furthermore, the great amount of data to be handled online by a single control centre may jeopardise the security of the energy supply. A different operation approach is thus required.

New distributed operation and control schemes are currently being explored to allow the insertion of distributed generation in the energy distribution network. This paper presents one of them, based on a Multi Agent System (MAS). The model of the distribution network is described in Section 2, which also presents the applied multi-agent system. Section 3 outlines the agent strategies and the simulation framework. Preliminary results obtained with this approach are presented and discussed in the Section 4. Section 5 summarises this contribution with concluding remarks.

2. Network model and Multi-Agent System

A model of the distribution network has been established. Its constituting elements are:
- Feeders representing a virtual energy source (either connected to the high-voltage transport network and lowering the electrical power to medium-voltage, or dispersed generators).
- Passive intermediate stations.
• End stations (cabinets) representing network loads. These stations lower the electrical potential to its final value and eventually feed the consumers through point-to-point power lines.

• Electrical links characterised by a flow capacity and a loss factor.

Distribution networks are traditionally operated in an arborescent or “open-loop” mode. Among all the electrical links constituting a meshed network, a portion is selected to form a radial configuration (the active links). Each link can be active or inactive as a result of the selection.

To limit its complexity, the model has been simplified in many points. All currents are assumed direct and continuous. Losses are taken into account, but voltages are assumed raised to the nominal value at the end of each link. The computation of the load-flow [1], which permits to know how much power must be injected into the network to feed the demand and compensate the losses, is approximated using a one-pass algorithm.

Due to several physical constraints (e.g. thermal limits, voltage drop), selection of active links cannot be made arbitrarily and must fulfil strict criteria. Additionally, an optimisation can be done with respect to several factors (e.g. losses and failure risk). Since the optimal solution cannot be found analytically, heuristic methods are often used to solve this NP-hard problem [2, 3, 4].

However, most of these heuristics are available as static procedures only. They do not allow an on-line optimisation, which is nevertheless an important feature of the future network operation.

Furthermore, in order to maintain the security of the system, the following requirement must be fulfilled: information flow between elements should be guaranteed, synchronisation mechanisms provided, and reactivity of the constituting elements should be high. If the number of DG sources present in the network is too high, traditional centralised off-line algorithms may not fulfil these requirements, due to scalability problems. The high reactivity is particularly important given that electrical energy is a non-storable commodity. The production should equal the consumption at any operation moment to preserve the stability of the system.

In order to satisfy these conditions, an on-line and decentralised network control scheme is proposed. A multi-agent system [5, 6] is built according to the aforementioned network model (depicted in Figure 1). An agent is assigned to each node. Agents are of three types: feeder agent (FA), load agent (LA), and neutral agents (NA). Neutral agents are placed in intermediate nodes where neither injection nor consumption is done. The network in then split in zones organised around each energy source. An agglomeration of one feeder and its loads constitute such a zone. FA acts as zone master.

Agents behave according to different objectives. FAs are active agents trying to maximise their profits while keeping a security margin. They gather consumers to reach a minimal profitability threshold, but will refuse new consumers or eject existing ones when approaching their maximal capacity. Each FA also tries to optimise the radial configuration of the network within its own zone, to minimise the losses and therefore augment its profits. LAs are passive agents, following the instructions of their zone master in order to secure their supply. NAs are passive too and only forward the messages along the topology.

At the beginning of its life, each agent knows only the data of the network located in its immediate neighbourhood, to which it has links attached. Additionally, each LA and NA knows which of its incident link is the uplink, i.e. the one through which it is connected to a feeder. As algorithm proceeds, agents gain additional data from other agents and use this information to fulfil the four following goals:

• Match the demand and the offer between feeders and loads
• Compute the load flow for the zone
• Propose to neighbouring zones a load exchange
• Optimise the configuration within one zone

Agents share no common time reference; therefore, no global synchronisation is possible. Nevertheless, since all changes are independent, agents are free to apply change at any time (hot plug). Is this case, the operation of the network in each zone can be performed on-line and in parallel to other zones. This enhances the reactivity of the system, and enables rapid adaptations whenever the situation changes.

All agents are assumed independent, to avoid possible competitor-related issues and provide information protection and fairness.
3. Strategies and Simulation Framework

3.1 Agent strategies

Feeder agents are in charge of maintaining the network located in their zones in a normal state. Therefore, they must periodically update their knowledge of the zone in order to adapt their power injection. To do so, they launch a zone-state exploration procedure.

- **Zone-State Exploration Procedure**
  
  **Goal:** update the topological and electrical information about the actual zone whose initiating feeder agent is the master.

  The procedure is illustrated in Figure 2. In the forward part, the feeder sends a message over each active adjacent link requesting the information about the current states of attached nodes. Each non-leave node receiving this message will recursively forward it further to adjacent active links and wait for the responses. When a leave of the zone arborescence is reached, the backward part of the procedure begins. Each leave sends a response containing its actual consumption and the characteristic of its uplink to its father node. Recursively, the non-leave node agents will collect the information of their son nodes and store it locally. When all excepted answers have been collected, they are aggregated inside one message and forwarded to the next father node. Finally, the feeder agent receives the whole information about the actual state of the zone. It can then apply the load flow algorithm to calculate the amount of power it has to inject into each adjacent link, and thus the total power it is supposed to produce.

- **Zone Network Reconfiguration Procedure**
  
  **Goal:** recompose the set of links forming a radial configuration towards all loads of the zone, in order to limit the losses and/or to avoid overtaking the link capacity.

  This procedure uses the information from the zone state exploration. Within all links (active or inactive) reachable in the zone, FA tries to establish a new link set which satisfies the radial configuration condition in order to allow a full service of each node while keeping the load of the feeder in its normal operating state. If a new link set is identified to provide a better performance than the actual set, switching operations are communicated to all NAs and LAs of the zone. Once the changes have been committed, a new zone state exploration procedure is launched.

- **Consumer Exchange Procedure**
  
  **Goal:** stay in the nominal operation range by either proposing “assistance” to neighbouring zone master (to gather new consumers) or on the contrary by requesting them “assistance” (to eject exceeding consumers).

  This procedure is launched if the result of the zone state exploration procedure and of the load flow computation reveals a mismatch between the generation possibilities and the consumption. This procedure includes the negotiations with the feeder agents of the neighbouring zones. Again, the procedure is accomplished in two parts: a forward and a backward information processing. The processing scheme is illustrated in Figure 3.

If total requested load does not match the desired operational range, or if load flow reveals that actual configuration causes important losses, FA may initiate one of the following procedures.
reaching the master of the neighbouring zone. The latter receives the proposition, analyses if it can meliorate its actual situation, and sends its response, which follows the same way in the other direction. Finally, the initiator receives a list of consumers susceptible leave or join the zone. From all the responses the quality of a new possible network state is evaluated using simple scoring rules, and the zone agent commits to the best proposition, if one exists. Again, a change is followed by a new zone state exploration procedure.

3.2 Algorithm complexity and convergence, network security

All procedures use a hierarchical messaging scheme. Within one phase, each agent except the initiator receives exactly one message and emits exactly one message. The total number of message $N$ emitted during one procedure is thus bounded by

$$N \leq 2(n_I-1)P$$  \hspace{1cm} (1)$$

where $n_I$ is the number of agents involved in the procedure and $P$ is the number of phases of the procedure. $n_I$ is bounded by the total number of nodes present in the network. $P=3$ is the worst case, corresponding to the following sequence: assistance request, changes commitment, and information update. Therefore, the total message complexity per procedure is $O(n_I)$.

The total number of procedures is variable and difficult to approximate. It depends greatly on the state of the network and its variability. However, assuming no changes in the consumptions and/or production in the network (i.e. no periodical zone exploration procedures), the algorithm is convergent since procedures are launched only if directly profitable changes are identified. The system will thus eventually reach a state which can no longer be improved (local optimum).

While performing the network reconfiguration, the following condition is respected: a node “unplugs” its feeding link (uplink) and plugs it to another neighbour. Using this rule the radial topology is conserved. An agent engaged in one procedure is locked and can not enter into another procedure. Concurrent modifications in a single zone are thus never committed. This avoids unanticipated combination of two independent changes. Furthermore, the convergence propriety of the algorithm avoids network instabilities at the electrical level.

3.3 Simulation framework

The presented approach has been tested by simulation means, and a simulation framework has been developed. Framework has been implemented from scratch using the Java language. A collection of Java objects were created first to model an electrical distribution network. Classes providing graphical interfaces for display and edition have been then provisioned. A Graphic User Interface has also been created to outlook the algorithm results. Eventually, agents have been implemented.

Each agent is executed by a separated java thread and communicates with other agents using a message-passing system.

Framework acts as an interface between the physical representation of the system and the agents, providing a restricted access to some local topological information (i.e. an agent cannot access the property of any other element of the network at any time). The framework is responsible for launching all agents that will operate in the network and collection the logging information produced by each agent. It also enables the messages exchange between the direct neighbours (marshalling, queuing of multiple message reception), using the Java’s TCP/IP stack (Figure 4). The following communication format is used: a message contains sender’s and receiver’s indexes, a message’s type and any object.

![Figure 4. Agents communicate with their peers and access to the local network information using the simulation framework.](image-url)

4. Results

The approach has been confronted to several static network situations, with pre-configured zones. When the simulation begins, feeder agents explore their zone and decide to launch procedures.

The Zone State Exploration Procedure and the Consumer Exchange Procedure have been tested and validated with simple test cases, as the one depicted in Fig. 5. In this extremely simplified case, feeder F_A should...
logically feed consumer \( C_\text{A} \) and feeder \( F_\text{B} \) consumer \( C_\text{B} \). However, network has been voluntarily preconfigured in a bad way: \( F_\text{A} \) is feeding both consumers and is overloaded, while \( F_\text{B} \) has no consumer and has exceeding capacity (Figure 5a). As soon as agents are launched, either \( \text{A} \) will ask \( \text{B} \) for help, or \( \text{B} \) will propose some help to \( \text{A} \). In both cases, algorithm converges in to the normal and optimal operation mode (Figure 5b).

To test the Zone Network Reconfiguration Procedure, the approach has been used for the case presented in [7], where a feeder failure brings the network to a critical state. The agent of the remaining feeder is detecting the problem and solves it applying inner zone reconfigurations. Algorithm converges to the same solution as the one presented in [7].

Eventually, the system has been tested with a more realistic test case: a circular open-loop distribution network composed of 6 feeders, 15 end-stations, and 15 intermediate stations. The network topology is shown in Figure 6. This circle models a peripheral network of feeders located outside a virtual agglomeration with distribution network penetrating inside the districts. The initial network condition is as follows: three feeders and three links are overloaded. After several rounds of procedures and exchanges, an acceptable configuration is found: none of the feeders is overloaded and only one link remains congested. Algorithm stops when no additional profitable changes can be made. Since all agents behave independently and share no time reference, the order in which the various procedure are started is not defined and depends on the way the Java Virtual Machine allocated CPU resources to the various threads. Therefore, the number of messages required to reach the convergence point is very variable (between 350 and 2000). However, in all the experiments, same convergence state has emerged.

While encouraging, these results are only preliminary and much work remains to be done to clearly validate the approach. Furthermore, the scheme suffers strong limitations, in particular since agents are not synchronised and only local search is achieved. The situation depicted and described in Figure 7 explicitly shows these shortcomings. The used links are overloaded due to their technical characteristic, i.e. high losses. Solution is straightforward: disconnect the links a and b and connect links c and d. However, both switching should occur synchronously. Otherwise, one of the feeders will be temporarily in a worst situation, which needs to be avoided.

5. Conclusions

As the energy sector liberalisation proceeds, the market model will gradually substitute the state monopolies over the energy production and distribution. This encourages the distributed generation, especially the renewable energy sources, to be installed in the energy-distribution networks. This change will present a challenge to network operation and control strategies.

With the introduction of multiple distributed energy sources, amount of data required to describe the network drastically increases. A control centre operating in a traditional centralised mode may need a lot of time to process the measurements and deliver the results, which may be already out of date. Such approach may
jeopardise the supply security and eventually lead to black-outs.

The use of distributed optimisation algorithms for the application in the electrical energy sector is thus being widely researched.

In this contribution, a method for the electrical distribution network control using Multi-Agent System is proposed. This method relieves congestions while feeding electrical loads by an on-line assessment of a new network configuration. The reconfiguration is then done within the specified technical and operational constraints and considering the minimum switching operations.

References


