
This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Fattaheian-Dehkordi, Sajjad; Jooshaki, Mohammad; Abbaspour, Ali; Fotuhi-Firuzabad, Mahmud; Lehtonen, Matti

Transactive-based control algorithm for real-time energy imbalance minimisation in microgrids

Published in:
CIRED - Open Access Proceedings Journal

DOI:
[10.1049/oap-cired.2021.0113](https://doi.org/10.1049/oap-cired.2021.0113)

Published: 01/09/2020

Document Version
Publisher's PDF, also known as Version of record

Published under the following license:
CC BY

Please cite the original version:
Fattaheian-Dehkordi, S., Jooshaki, M., Abbaspour, A., Fotuhi-Firuzabad, M., & Lehtonen, M. (2020). Transactive-based control algorithm for real-time energy imbalance minimisation in microgrids. *CIRED - Open Access Proceedings Journal*, 2020(1), 549-552. <https://doi.org/10.1049/oap-cired.2021.0113>

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Transactive-based control algorithm for real-time energy imbalance minimisation in microgrids

Sajjad Fattaheian-Dehkordi^{1,2} ✉, Mohammad Jooshaki^{1,2},
Ali Abbaspour², Mahmud Fotuhi-Firuzabad^{1,2}, Matti Lehtonen¹

¹Department of Electrical Engineering and Automation, Aalto University, Helsinki, Finland

²Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

✉ E-mail: Sajjad.fattaheiandehkordi@aalto.fi

Abstract: Modern power systems would compose of networked microgrids (MGs) operating independently. Respectively, MGs' control units (MCUs) are responsible for optimising the operation of independent agents associated with local resources to maximise the social welfare of the system. In this regard, agents schedule their respective resources with the aim of maximising their profits; while MCU as a mediator entity strives to facilitate the flexibility of service exchange among the agents. In MGs, renewable energy sources (RESs) as potential sources of energy confront with uncertainty originated from their dependence on meteorological resources. Consequently, MGs would confront energy imbalance in real time as a result of probable inaccuracies corresponding with forecasting the power production of RESs in the day-ahead market. To tackle this issue, a transactive-based framework is developed in this study that enables MCUs to incentivise the cooperation of agents scheduling flexible resources in minimising energy imbalances in real time. Correspondingly, MCU offers bonuses as transactive signals to local agents to contribute in minimising the energy imbalance; which consequently results in improving the MG flexibility. Finally, the developed framework is implemented on an MG composed of independent agents scheduling flexible resources to investigate its effectiveness in minimising the energy imbalance in MGs.

1 Introduction

Microgrids (MGs) as independent entities have been introduced to enable the decentralised control of distribution systems. Furthermore, the development of distributed generation units that could be integrated into distribution systems and operated by independent agents has facilitated the expansion of MGs in the system. MGs' control units (MCUs) manage the scheduling of local resources operated by their respective agents and so determine the power exchange with the main grid. In this respect, each agent strives to maximise its respective profit; while MCU attempts to efficiently coordinate the operation of agents and maximises the overall profit. Consequently, MGs have facilitated the integration of independently operated local resources in modern power systems.

One of the potential primary power generation resources in MGs would be renewable energy sources (RESs) like wind power and photovoltaic (PV) units. The increasing rate of RESs installations in local systems is mainly originated from the rising environmental concerns. However, the stochastic and intermittent nature of RESs could lead to operational issues due to potential inaccuracies associated with their respective power generation prediction procedures [1, 2]. This could eventually result in real-time (RT) energy imbalance in MGs and therefore expose them to RT costs in order to compensate for the dismissed power generation by RESs. Consequently, the profits associated with RESs agents could be significantly decreased. To tackle this issue, a new framework needs to be developed in order to enable the MCUs to exploit the operational scheduling of flexible local resources in a way that the cost associated with RT energy imbalance in the MG decreases.

Recently, transactive energy (TE) is introduced as a novel control concept that facilitates the management of multi-agent systems [3]. Economic-based mechanisms are employed in TE in order to

efficiently coordinate the operation of independent agents to address utilities' operational objectives. In other words, the control mechanisms in TE enable the participation of independently operated local resources in the operation of power systems. In central control frameworks, a central entity is responsible for the direct operational management of all local resources; while the distributed control framework in TE is based on designated values (i.e. economic transactions) rather than direct control signals. In this regard, the detailed information required for the implementation of the central control frameworks would not be essential in TE-based control schemes. This control mechanism facilitates the coordination of independent agents who are unwilling to cede complete control of their resources to the system operator. As a result, the TE concept could be taken into consideration to develop a coordination mechanism to incentivise independently operated flexible resources in an MG to contribute to minimising the cost associated with RT energy imbalances. This approach would finally decrease the dependence of MGs on the main grid to compensate for the power exchange differences between RT and day-ahead (DA) operational planning; which results in improving the reliability and security of MGs [4].

Qiu et al. [5] have employed the TE concept in order to conduct resource scheduling in a virtual power plant. A TE-based framework is developed in [6] to schedule resources in a distribution system by considering the system operator as a mediator entity. TE concept is taken into account in [7] to manage a system considering storage units and demand response. Liu et al. [8] have utilised TE to coordinate the operation of networked MGs. The authors in [9] have deployed TE to conduct the energy management of residential buildings as well as provide flexibility services for the main grid.

The applications of the TE concept in incentivising independently operated responsive resources to contribute to the efficient operation of smart grids are investigated in several pilot projects [10–12].

Researchers in the RENnovates project [10] have employed TE to incentivise flexible demands in residential houses to contribute to the alleviation of network congestions. In this research project, the communication between the aggregators and prosumers is provided utilising a smart grid field test. In this context, the developed framework in [10] aims to facilitate the re-scheduling of end-user loads to efficiently manage distribution systems.

Despite various studies, which have been conducted on energy management of MGs as well as coordination of multi-agent systems; to the best of the authors' knowledge, coordination of independently operated agents to minimise the RT energy imbalance has not yet been investigated in the previously proposed methodologies. In this regard, a new procedure is developed in this paper, in which, MCU announces a transactive signal to different flexible agents in the system with the aim of incentivising their contribution in RT energy imbalance mitigation. The developed transactive signal is associated with the RT prices and so would motivate the flexible units to contribute to mitigating the RT energy imbalance in the MG. It is noteworthy that the proposed procedure would also decrease the dependency of MGs on the main grid to address the gap between demand and supply; which would eventually result in improvement of the power system from the flexibility perspective.

In this paper, the multi-agent model of the system and the proposed transactive-based control framework for the coordination of flexibility exchange among the agents will be discussed in Sections 2.1 and 2.2, respectively. The operational scheduling of local resources and interaction between MCU and agents are illustrated in these sections. Furthermore, the mathematical modelling of the proposed framework from the MCU's and agents' perspectives is described in Section 2.3. Finally, the results of implementing the proposed scheme on an MG with a multi-agent structure to coordinate the operation of independent agents in minimising the energy imbalance in the MG are presented in Section 3, followed by a conclusion in Section 4.

2 Methodology

2.1 System modelling

Future power systems would compose of networked MGs, which are independently operated to maximise their respective profits. In this regard, scheduling of local resources in each MG would be conducted by their respective agents; while MCU is responsible for the coordination of the MG's agents to maximise the overall profits. In this context, besides keeping the privacy of customers, the procedure of collecting and transmission as well as the computational burden associated with the analysis of operational data of local resources would be minimised.

In this structure, each agent of the system is considered to be responsible for the scheduling of a kind of local resources in DA and RT markets with the aim of maximising its respective profits. Additionally, MCU strives to coordinate the operation of agents as well as activates flexible services to support the main grid. In this regard, it is assumed that MCU employs transactive control signals in order to stimulate the cooperation of independent agents. In this context, a simplified model of transactive control structure in an MG with the multi-agent structure is presented in Fig. 1.

2.2 Proposed TE-based coordination framework

As mentioned, MCUs are responsible for the coordination of operational scheduling of agents with the aim of minimising the overall operational costs; while independent agents strive to maximise their respective profits. In this paper, it is considered that scheduling of RESs, electric storage systems (ESSs), dispatchable generations (DGs), flexible loads and electric vehicles (EVs) in DA, as well as RT markets, are conducted by independent agents. In this regard, RESs agents could confront RT costs due to errors in forecasted power production during

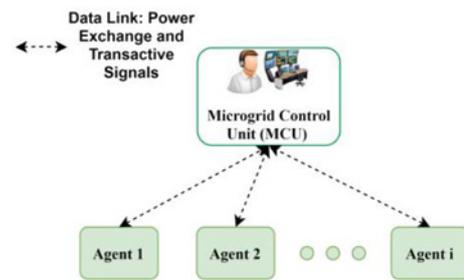


Fig. 1 Multi-agent structure of the MG

participation in the DA market. As a result, MCUs as mediator entities could employ bonuses as transactive signals to incentivise agents operating flexible resources to re-schedule their local resources with the aim of minimising RT costs. In other words, MCUs facilitate the exchange of flexibility services between local agents. In this regard, the cost associated with RESs' agents would be less than the cost associated with the power exchange in the RT market. As a result, this procedure benefits both RESs' agents and the agents operating flexible units; which would result in maximisation of overall social welfare. Based upon the previous discussions, a simple stepwise flowchart of the proposed framework is shown in Fig. 2. Regarding the proposed algorithm, the framework is conducted iteratively and the MCU increases the announced bonuses in each step until approaching the maximum amounts or the energy imbalance becomes zero in the RT. It is noteworthy that the proposed algorithm is not limited to energy imbalance caused by RESs and so could be conducted by MCUs to efficiently deal with RT energy imbalance in the MGs.

2.3 Mathematical formulation

Regarding the proposed transactive framework, MCU announces bonuses (i.e. $b_t \times \Delta P_t^{\text{Agent}}$) to agents of the MG in each time period to incentivise their contribution in minimising the RT energy imbalance. Noted that the bonuses paid by MCU would be compensated by the RESs agent as the responsible party for RT energy imbalance. In this regard, announced bonuses at each time interval (i.e. b_t) would be limited by the difference between the prices associated with selling/purchasing energy from the main grid. In the following sections, the optimisations conducted by agents scheduling flexible resources in the MG are illustrated.

2.3.1 Scheduling of flexible demands: The optimisation conducted by agents responsible for scheduling flexible demands

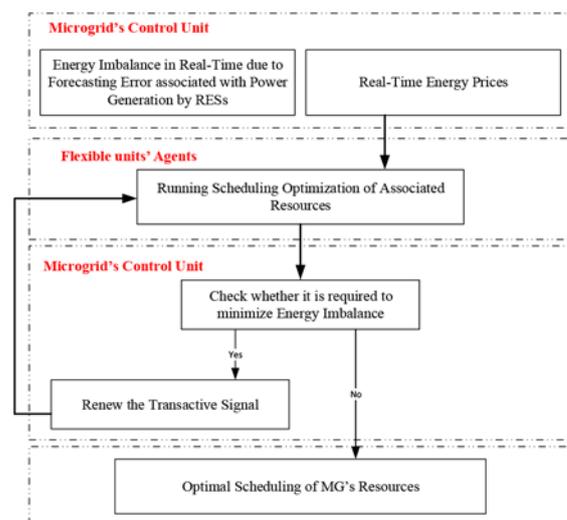


Fig. 2 Flowchart of the proposed framework

in the RT is modelled as follows:

$$\begin{aligned} \text{Max} \quad & \sum_{k \in I^{\text{Demand}}} ((b_t - \lambda_t) \Delta P_{k,t}^D) \\ & + \sum_{t' \in [t+1, t+T]} \sum_{k \in I^{\text{Demand}}} ((-\lambda_{t'}) \Delta P_{k,t'}^D) \end{aligned} \quad (1)$$

Subject to operational constraints of flexible load demands in $[t, t+T]$ time periods. Regarding the objective formulation (1), it is considered that the agent considers the future T time intervals in the optimisation conducted for scheduling the flexible load during RT in time interval t . In the optimisation model, λ_t , $\lambda_{t'}$ and $\Delta P_{k,t}^D$ present the RT price of power exchange with the main grid at t , the forecasted RT price of power exchange with the main grid at t' , and the change in the power requested by load k at time interval t , respectively. Moreover, the objective function (1) aims to maximise the profits of the demand agent.

2.3.2 Scheduling of ESSs: The optimisation conducted to re-schedule ESSs in RT is formulated as follows:

$$\begin{aligned} \text{Max} \quad & \sum_{k \in I^{\text{ESS}}} ((b_t - \lambda_t) \cdot (\Delta P_{k,t}^{\text{Ch,ESS}} - \Delta P_{k,t}^{\text{Dis,ESS}})) \\ & + \sum_{t' \in [t+1, t+T]} \sum_{k \in I^{\text{ESS}}} ((-\lambda_{t'}) \cdot (\Delta P_{k,t'}^{\text{Ch,ESS}} - \Delta P_{k,t'}^{\text{Dis,ESS}})) \end{aligned} \quad (2)$$

Subject to operational constraints of ESS units in $[t, t+T]$ time periods. The agents managing ESS units consider the future T time intervals in their operational optimisation for the t th time period. Regarding the optimisation model, $\Delta P_{k,t}^{\text{Ch,ESS}}$ and $\Delta P_{k,t}^{\text{Dis,ESS}}$ show the change in the power charging/discharging of the k th ESS at time interval t , respectively. Moreover, the objective function (2) maximises the profit of the ESS agent considering the bonuses offered by the MCU and RT prices of energy exchange with the upper-level network.

2.3.3 Scheduling of DG units: DG units are one of the flexible resources that could be re-scheduled to provide flexibility services for minimising the RT energy imbalance in the MG. In this regard, the optimisation model conducted by agents responsible for the operation of DGs considering the bonuses announced by MCU could be formulated as follows:

$$\begin{aligned} \text{Max} \quad & \sum_{k \in I^{\text{DG}}} ((b_t + \lambda_t) \cdot \Delta P_{k,t}^{\text{DG}} - C_{k,t}^{\text{DG}} \cdot \Delta P_{k,t}^{\text{DG}}) \\ & + \sum_{t' \in [t+1, t+T]} \sum_{k \in I^{\text{DG}}} (\lambda_{t'} \cdot \Delta P_{k,t'}^{\text{DG}} - C_{k,t'}^{\text{DG}} \cdot \Delta P_{k,t'}^{\text{DG}}) \end{aligned} \quad (3)$$

Subject to operational constraints of DG units in $[t, t+T]$ time periods. In the optimisation model, the operational costs of DG units and the change in the power production of the k th DG unit are correspondingly indicated by $C_{k,t}^{\text{DG}}$ and $\Delta P_{k,t}^{\text{DG}}$. Finally, the objective function (3) aims to maximise the profits associated with DG units.

2.3.4 Scheduling of EVs: EVs play a significant role in modern power systems and could be re-scheduled to provide flexibility services on the condition that the announced bonuses by MCU maximise their respective profits. In this paper, it is conceived that the operational management of EVs is conducted by an independent agent; which strives to maximise its respective profits as follows:

$$\begin{aligned} \text{Max} \quad & \sum_{k \in I^{\text{EV}}} ((b_t - \lambda_t) \cdot (\Delta P_{k,t}^{\text{Ch,EV}} - \Delta P_{k,t}^{\text{Dis,EV}})) \\ & + \sum_{t' \in [t+1, t+T]} \sum_{k \in I^{\text{EV}}} ((-\lambda_{t'}) \cdot (\Delta P_{k,t'}^{\text{Ch,EV}} - \Delta P_{k,t'}^{\text{Dis,EV}})) \end{aligned} \quad (4)$$

Subject to operational constraints of EV units in $[t, t+T]$ time periods. The objective function (4) strives to maximise the profit of EV units; where $\Delta P_{k,t}^{\text{Ch,EV}}$ and $\Delta P_{k,t}^{\text{Dis,EV}}$ model the change in power charging/discharging of the k th EV unit at time t .

3 Results

The developed framework is implemented on an MG composed of independent agents operating their respective resources in order to investigate its effectiveness in minimising the RT energy imbalances. In this regard, the forecasted and RT power productions by RESs in the MG are shown in Fig. 3; which shows that the MG would expose to RT prices for efficiently managing the energy imbalances associated with RESs in RT. Consequently, MCU would announce bonuses as transactive signals to incentivise the agents to re-schedule their flexible resources in a way that the RT energy imbalances minimise. In this regard, the operational scheduling of DGs in DA and RT is shown in Fig. 4. It is noteworthy that the differences between RT and DA scheduling of flexible units rely on the announced transactive signals; as the operational characteristics of resources as well as the prices of selling/purchasing energy to/from the upper network are considered to be similar to DA. In this regard, the overall flexible demand is increased in hour 9 by 6.95 MW; followed by the same amount of power decrease in hour 15. Consequently, the flexible demand agent provides flexibility service in hour 9; while ensuring the required amount of energy during 24 h is supplied. Moreover, the charging of EVs is increased by 0.35, 0.85 and 5.5 MW in hours 4, 8 and 9; while, the power charging is decreased by 5.5,

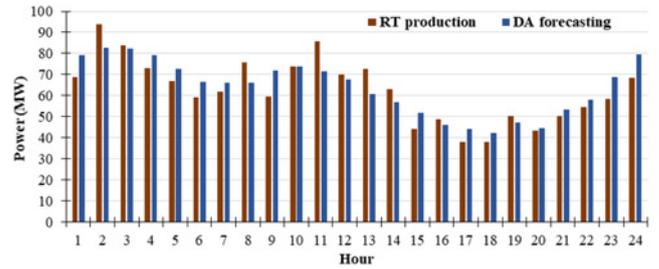


Fig. 3 Power production by RESs

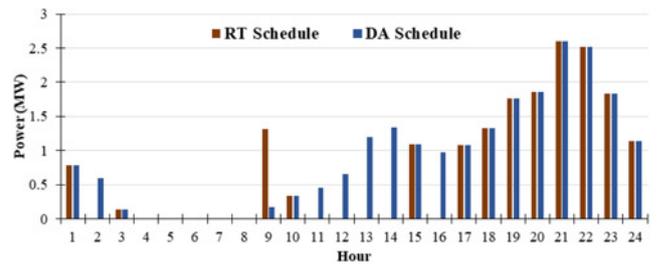


Fig. 4 Power production by DG units

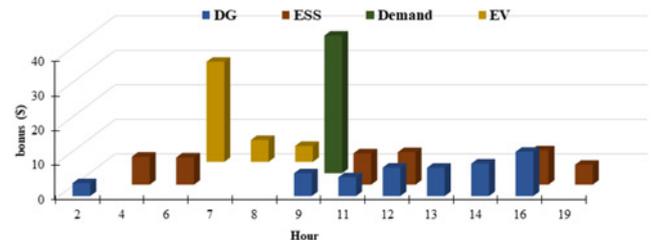


Fig. 5 Bonuses paid to agents

and 1.2 MW in hours 6 and 7. Consequently, re-scheduling of flexible resources has benefited the MG; while the energy consumption by each agent remains similar to the DA scheduling. Finally, the bonuses paid to each agent of the MG; which are contributed to minimising the energy imbalance associated with power production by RESs in RT are shown in Fig. 5. In this regard, the proposed framework improves the flexibility of the MG; which finally decreases its dependence on the main grid.

4 Conclusions

In this paper, a new transactive control scheme is developed in order to minimise the energy imbalance in an MG with a multi-agent structure. In this regard, MCU as the entity responsible for the coordination of independently operating agents employs bonuses as transactive signals in order to incentivise the agents to re-schedule their flexible resources. This framework facilitates the flexibility of service exchange among the agents to minimise the energy imbalance caused by uncertainties associated with power productions by RESs.

The developed framework is implemented on an MG composed of independent agents scheduling RESs, flexible demands, DGs, ESSs and EVs; which shows the application of the approach in minimising the energy imbalance in the MG. It is noteworthy that the interaction between MCU and agents in the proposed framework is limited to accumulated power requests and transactive signals to address the privacy concerns in multi-agent systems. Finally, the proposed approach would result in improving the flexibility of MGs; which eventually improves the flexibility of power systems.

5 References

- 1 Tavakkoli, M., Fattaheian-Dehkordi, S., Kasmaei, M. P., *et al.*: 'Bonus-based demand response using Stackelberg game approach for residential end-users equipped with HVAC system', *IEEE Trans. Sustain. Energy*, 2020, **12**, pp. 234–249
- 2 Kamrani, F., Fattaheian-Dehkordi, S., Abbaspour, A., *et al.*: 'Investigating the impacts of microgrids and gas grid interconnection on power grid flexibility'. 2019 Smart Grid Conf. (SGC), Tehran, Iran, 2019, pp. 1–6
- 3 Khorasany, M., Mishra, Y., Ledwich, G.: 'Market framework for local energy trading: a review of potential designs and market clearing approaches', *IET Gener. Transm. Distrib.*, 2018, **12**, pp. 5899–5908
- 4 Fattaheian-Dehkordi, S., Tavakkoli, M., Abbaspour, A., *et al.*: 'Distribution grid flexibility-ramp minimization using local resources'. 2019 IEEE PES Innovative Smart Grid Technologies, Europe, 2019, pp. 1–5
- 5 Qiu, J., Zhao, J., Yang, H., *et al.*: 'Optimal scheduling for prosumers in coupled transactive power and gas systems', *IEEE Trans. Power Syst.*, 2018, **33**, (2), pp. 1970–1980
- 6 Renani, Y.K., Ehsan, M., Shahidehpour, M.: 'Optimal transactive market operations with distribution system operators', *IEEE Trans. Smart Grid*, 2018, **9**, (6), pp. 6692–6701
- 7 Nunna, H.S.V.S.K., Srinivasan, D.: 'Multiagent-based transactive energy framework for distribution systems with smart microgrids', *IEEE Trans. Ind. Inf.*, 2017, **13**, (5), pp. 2241–2250
- 8 Liu, W., Zhan, J., Chung, C.Y.: 'A novel transactive energy control mechanism for collaborative networked microgrids', *IEEE Trans. Power Syst.*, 2019, **34**, (3), pp. 2048–2060
- 9 Nizami, M.S.H., Hossain, J., Fernandez, E.: 'Multi-agent based transactive energy management systems for residential buildings with distributed energy resources', *IEEE Trans. Ind. Inf.*, 2020, **16**, . pp. 1836–1847
- 10 Council, T.: 'Gridwise transactive energy framework version 1.0'. Tech. Rep., The GridWise Architecture Council, 2015
- 11 Kok, J.K., Warmer, C.J., Kamphuis, I.: 'Powermatcher: multiagent control in the electricity infrastructure'. Proc. of the Fourth Int. Joint Conf. on Autonomous Agents and Multiagent Systems, Utrecht, Netherlands, 2005
- 12 Soares, A.R., De Somer, O., Ectors, D., *et al.*: 'Distributed optimization algorithm for residential flexibility activation – results from a field test', *IEEE Trans. Power Syst.*, 2019, **34**, pp. 4119–4127