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Application of game theory in electrical engineering on the example of transformer tap control

Abstract. *The paper presents an attempt to use game theory to voltage regulation by controlling the transformer's taps. The receiver is an industrial process for which it is necessary provide stability of the supply voltage, regardless of changes in the grid. Appropriate formulation of payouts for playes(agents) resulted in finding the optimal solution, based on Nash's equilibrium under both constraints: minimizing voltage error and minimizing the number of tap switching operations. The Gambit software and Python programming language were used.*

Streszczenie. *W pracy przedstawiono próbę wykorzystania teorii gier do regulacji napięcia poprzez sterowanie odczepami transformatora. Odbiornikiem jest proces przemysłowy, dla którego konieczne jest zapewnienie stabilności napięcia zasilania, niezależnie od zmian w sieci. Właściwe określenie wypłat dla agentów (graczy) zaowocowało optymalnym rozwiązaniem, wykorzystując równowagę Nasha przy uwzględnieniu warunków: minimalizacja błądu napięcia i minimalizacja wykorzystania przełącznika zaczepów. Wykorzystano oprogramowanie Gambit i język Python.* ***(Zastosowanie teorii gier w inżynierii elektrycznej na przykładzie sterowania zaczepami transformatora)***

Keywords: game theory application, voltage control, tap changing, regulation transformer
Słowa kluczowe: zastosowania teorii gier, regulacja napięcia, sterowanie zaczepami, transformator regulacyjny

Introduction

For many people, the first associations with game theory are gambling, strategies and nowadays computer games. However, the game theory can be classified as a mathematics branch. In the foreword to the Polish edition of the Straffin's game theory textbook [1], she was named a *mathematical theory of conflict*.

People have always considered potential strategies and solutions for the various games they played. The aim of these analyses was to find the moves in the game that were supposed to ensure victory. If a win of only one player means the failure of the remaining players, this is a zero-sum game. The mathematical description of zero-sum games was done by John von Neumann in the 1928 [3], and a book written together with economist H. Morgenstern [4] can be regarded as the beginning of modern, mathematical game theory. Von Neuman in [3] introduced a *mini-max* theorem, which has a wide range of applications, e. g. in computer games or in technical applications for solving some optimization problems.

After publication of [4], there has been a rapid development of this field of knowledge, although its application in economic sciences was mainly considered. It is worth to mentioning, that 12 Nobel Prizes have already been awarded for research related to game theory. The best-known Nobel Prize winner, perhaps through the movie *Beautiful mind* is John F. Nash. By introducing the idea of Nash's equilibrium, he made an important contribution to game theory. Besides fairly well described zero-sum games, many real-life phenomena can be represented with non-zero-sum games and cooperative games, where players can exchange information in order to achieve the highest possible outcomes for everyone [2]. To determine the strategies that are most beneficial for all players, Nash's equilibrium is necessary[5].

The game theory is currently used in many scientific fields: mainly in economics sciences, also social sciences or to analyze political issues [2]. Appropriately applied game theory approach can be very helpful to solving optimization problems, in multi-criteria or dynamic optimization. However, it is increasingly used in technical sciences, but not yet used too widely in technical sciences and has not yet found too many applications in electrical engineering. Several applications from the literature are presented in the next section.

The recent practical application of game theory

In the contexts of applying game theory in the control of voltage, authors found the following publications. Nguygen et al.[9] used game theory and Nash's bargaining solution to control voltage by controlling the flow of reactive power in distributed network. Two game scenarios have been proposed, both involving the electric utility company and the customers as players. According to simulations carried out by the authors, all players received benefits. The work by Zheng et al.[7] presents the use of cooperative game theory to control voltage based on coordination of reactive power sources. This work uses zone division and alliances. Individual rationality based cooperative game model are used to search efficient players in alliances to improve their control effect, while alliances play a noncooperative game, and the Nash equilibrium strategy allow zones to consider the interaction and coupling from others thus avoid voltage oscillation and overshoot. In [8] by Nassaj et al. has been presented a robust and novel scheme for maintaining voltage stability in power system by employing the cooperative game theory concepts and the obtained numerical results from simulations acknowledge the effectiveness and reliability of the presented algorithm.

No other original examples of the theory of games in electrical engineering have been found. All the above mentioned related works were based only on simulations and concerned voltage regulation on a wider scale of the distributed power system. Discussions on other engineering applications of game theory in power systems can be found in [6].

In the Przegląd Elektrotechniczny to date, two articles have been published about the application of game theory: Skrzypczyk [10] addresses the problem of a mobile vehicle navigation in case of a moving target and proposes a algorithm using the game theory that is robust to an uncertainty of data; Wu et al. [11] present the routing method using game theory applied in wireless ad hoc networks, when network node's routing cost must be in line with Nash equilibrium.

System description

The receiver for the application described in this article is a some real industrial process that requires the supply voltage to be stabilized within a specific range, making it independent from changes in grid voltage. Additionally, during the process it is advantageous to periodically raise and then, before the process is completed, lower the voltage in relation to the nominal mains voltage (see Fig. 1). This receiver

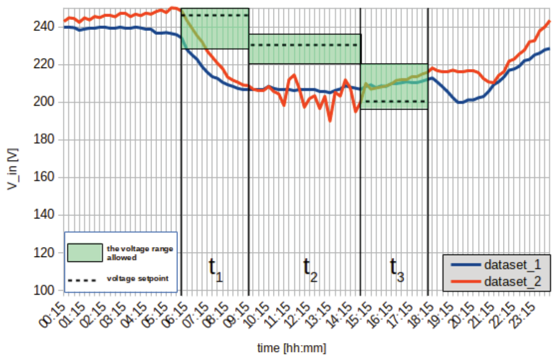

Fig. 1. Example grid voltage measurements, allowable voltage ranges for receiver and voltage set-points

is supplied with mains AC 3-phase 400/230V voltage. The voltage is regulated independently for each phase. A further description will be carried out for only one phase.

The mains voltage stabilization and voltage control during the process described above is performed by a regulation transformer with tap-changer working connected as autotransformer (see Fig. 2). The regulation transformer has a multiple tapping points and cooperates with dedicated tap-changer, which has a hybrid construction (contactors and auxiliary semiconductors part). The device is suitable for frequent on-load switching. The tap changer previously was controlled from the microprocessor controller, which operated a standard P-type control algorithm with hysteresis block.

The voltage control by tap-switching of transformers is based on the use of conventional controllers, e. g. proportional, hysteresis, etc. Examples of traditional regulators and possibilities for their advancement can be found in [13]. Nowadays, a voltage control, due to the fact that a large quantity of distributed energy sources and power electronics (switching mode) receivers are connected with traditional methods is becoming problematic. In [12] a review of some slightly modern can be found, e. g. with using fuzzy logic. More comprehensive ideas using game theory, coordination of zones where voltage needs to be controlled have already been shown in the previous section.

Further technical details will be omitted, because part of the described solution is related to the contract for industry carried out in the department and the authors cannot at this stage of the work reveal some technical solutions.

Problem definition

The standard control unit, previously operating with the on-load tap-changer, due to the large fluctuations of the grid voltage (see *dataset_2* on Fig. 1) and its rapid short-term changes, resulting from the connection of additional impulse energy receivers, no longer meets the requirements. Voltage management has become unsatisfactory and the use of the on-load tap-changer too frequent. A modification of the algorithm was necessary. In this paper, an attempt was made to solve the mentioned problem with a algorithm based on game theory.

Control objectives

The main requirement was to keep the output voltage within the desired range, while keeping the number of switching operations as low as possible. This constraints can be written down as follows: $min\,(\varepsilon_U)$, where $\varepsilon_U = \Delta U_{Out} - U_s$ is voltage regulation error; $min(\sum k)$, where k denotes the number of tap-changer switching operation in some period.

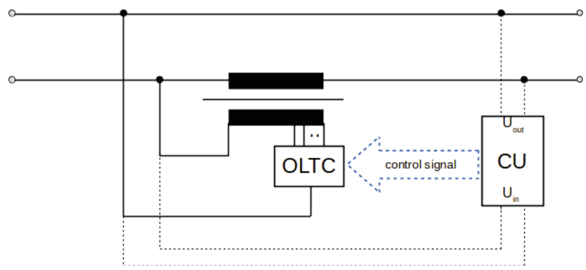

Fig. 2. View of regulation transformer circuit (only one phase is shown); *OLTC - on load tap-changer, CU - controller unit,* U_{in} *– input voltage,* U_{out} *– output voltage*

Game theory approach

To meet the above-mentioned requirements, two players (agents) have been defined driven by different strategies. The first player will try to keep the voltage error as low as possible, without considering the number of switching operations. The second player will want to make the minimum number of switching operations, not minimizing the voltage error but only trying to keep it within acceptable range.

The outcome function for both players is as follows:

$$W = -k|U_S - U_{Out}| + i(G - NS), \tag{1}$$

where k denotes a coefficient associated with the component related to minimizing voltage error, i is a coefficient associated with the component related to number of switching operations made. The outcome from this part is proportional to the difference between NS – the number of switching operations performed and G – the number of switching operations granted for regulation period . The coefficients k, i for players were selected manually and iteratively, these were used in turn various combinations from a certain set of values. According to the game theory, for a given set of factors, the game can be transformed into a form equivalent with other coefficients. The pair of coefficients $(k_1,\ i_1)$ and $(k_2,\ i_2)$ for both players are different, assuming the same outcome function for all players, they decide on the strategy chosen by the players.

The result of the game is the configuration of the transformer's taps (and corresponding binary control signal – see Fig. 1), depending on the game's course. The optimal solution corresponds to the Nash's equilibrium, which provides the highest payout for both players. The equilibria are computing using simplicial subdivision method. The Gambit [15] implements algorithm of van der Laan, Talman, and van Der Heyden [14].

The algorithm proceeds by constructing a triangulated grid over the space of mixed strategy profiles, and uses

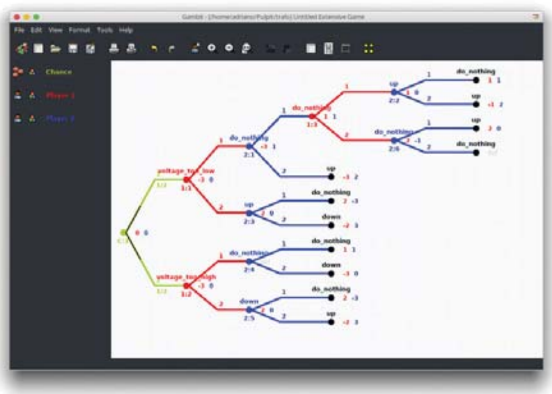

Fig. 3. Gambit program window during creating a game model in the tree view

Table 1. A available tap configurations, corresponding percentage voltage change, control signals, example output voltage at U_{In} = 230 V

percentage change [%]	-17,0%	-14,3%	-13,0%	-10,4%	-9,1%	-6,5%	-5,2%	-2,6%	2,6%	5,2%	6,5%	9,1%	10,4%	13,0%	15,7%	17,0%
control signal [bin value]	1100	1101	1111	1110	1010	1011	1001	1000	0000	0001	0011	0010	0110	0111	0101	0100
output voltage [V]	191	194	200	206	209	215	218	224	236	242	245	251	254	260	263	269

a path-following method to compute an approximate fixed point, which can then be used as a starting point on a refinement of the grid. The program continues this process until locating a mixed strategy profile at which the maximum regret is small. It begins with the centroid, and computes one Nash equilibrium.

To perform computation the *gambit-simpdiv* internal function were used. Gambit is a cross platform (Windows, mac OS, Linux) open-source tool for doing computation in game theory [15]. This software can be used to build, analyze and solve game models. Gambit has a graphical user interface that is helpful in building model and analyzing the game. The view of program window during the defining of a game in tree view was shown in Fig. 3. In the next step, the game can be resolved, with providing external data to the model by calling from the command line interface or using dedicated API in Python programming language [15]. The last of the methods was used.

Experiment I – method verification

To verify the correctness of the chosen approach in the first stage, simulations were performed using real measurement data. Measurement data were taken from the energy analyser and loaded from a CSV file. Every minute the game was triggered, and at each solver call the current voltage error was modified depending on the measurement values and payout values, taking into account the decreasing number of switching available to the player. The author's program in Python was responsible for the simulation process, its flowchart is shown in Fig. 4.

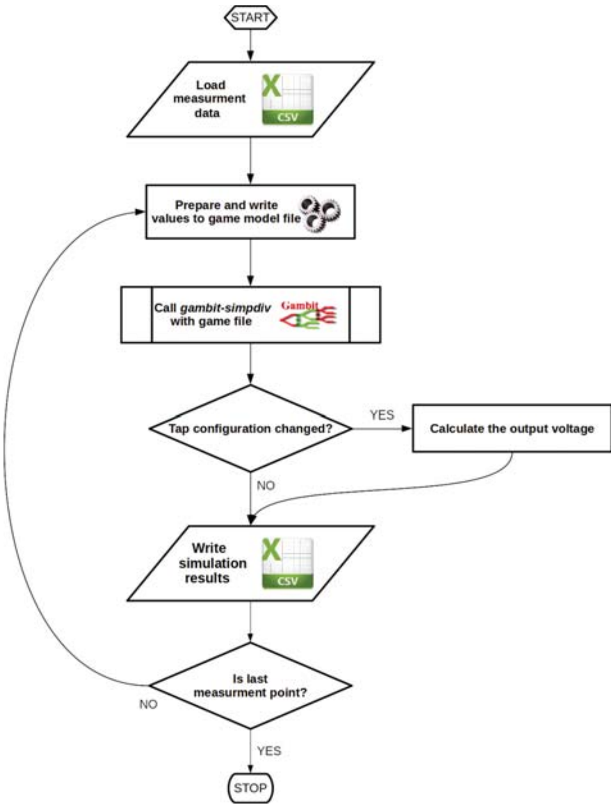

Fig. 4. The flowchart of python simulation program

The program loads the measurement points, called

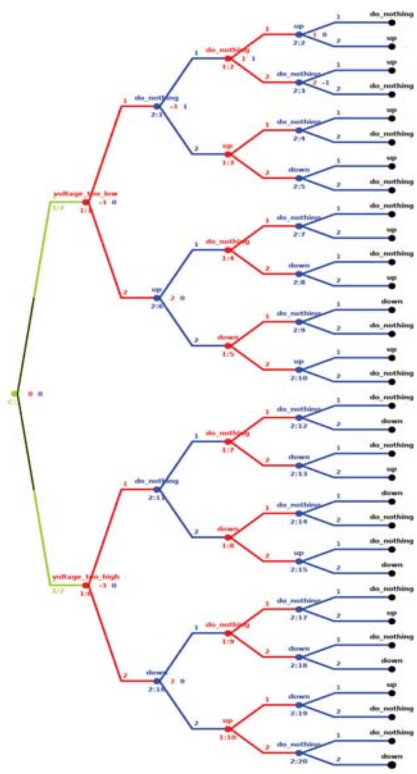

Fig. 5. Tree view of the game model

gambit-simpdiv function, compared the obtained configuration of tap-points and calculated the output voltage. The following game model was used at this phase (see Fig. 5): the game starts when the voltage has been measured, first it determines whether the voltage is higher or lower than the set point, then the first player decides whether the voltage should be raised or lowered. in the next turn, the second player determines whether to leave or change the setting made by the first player. In the next two moves, players decide again whether to improve the movement chosen by the opponent (lift or lower the voltage or do nothing). The outcome values for players in each node are calculated at each call of the game solver, depending on the current voltage error and the number of performed switching operations. In case of too low voltage, the game runs in a analogous way.

The results of the first simulation, where players controlled only two taps is shown in Fig. 6. As can be seen, for

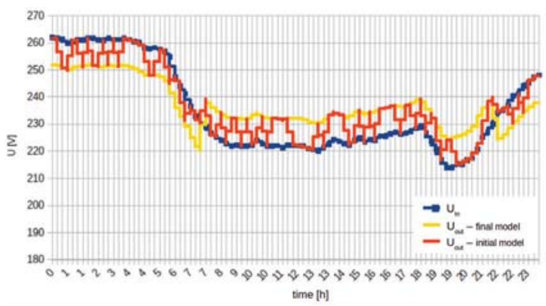

Fig. 6. Simulation results for simple game model and only 2-taps control

the first case (*initial_model*) switching took place too often, because component of the outcome related to voltage was too large. The benefits of minimizing the number of switching should have been increased (what was done*final_model*). Considering the ability to control only 2 taps (+6.6 %, 0, -6.5 %), it has been found that the method works correctly.

Experiment II – improved model, comparison

After confirming the correct functionality for two taps control, the game tree was upgraded. Added the ability to control all available taps, the player starting the game is selected randomly, so the game is not always started by a player with the same strategy. The component related to minimization of switching operation was further increased. The switching operation limit added, during the day, players have a limit of 20 and within an hour they can make a maximum of 5 switching. The method was compared on real data with a conventional, previously operating controller (see Fig. 7). For voltage regulation (Fig. 7a) the results are similar, acceptable and within the required range in both cases. The difference can be seen when comparing the number of switching operations (Fig. 7b). The game theory-based method works much better in this aspect.

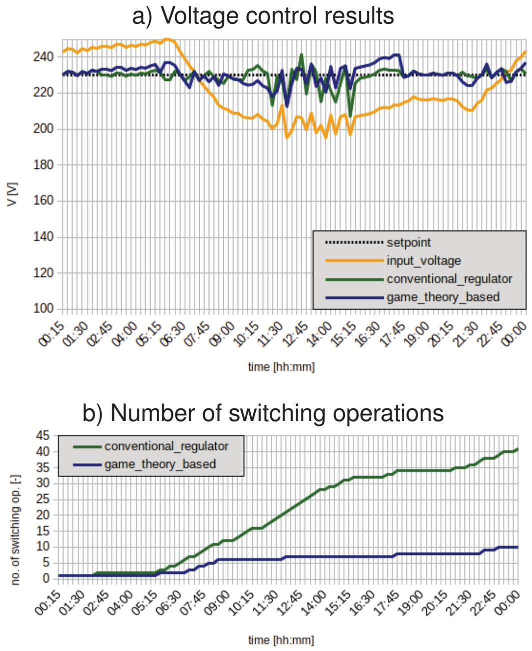

Fig. 7. Comparison of voltage control results (a) and number of switching operations (b)

Conclusion and future works

The developed method, in case of practical implementation requires further research and testing, however, for the analysed cases where the game strategy is described in a fairly simple way brings positive results. In particular, a great benefit can be gained by minimizing the number of switching operations and prolonging the life-time of the on-load tap-changer. The quality of the voltage regulation seems to be slightly worse, but it was within the acceptable range. During the second experiment, the voltage setpoint of 230V was used for comparison with the previous solution due to data available. The next step will be to test the operation including raised and lowered voltage zones from Fig. 1 on the real measurement data.

Practical implementation of game theory computational methods is possible and does not require high performance (can be implemented in a microcontroller), but can be labor-intensive. For testing on a real object (see Fig. 8), the authors are planning to use a single-board computer, e. g. a Raspberry PI [16]. The board, with Linux system, allows to use the developed simulation software with *Gambit* library after slight modifications. In the initial stage it is also possible to run in parallel with the existing controller in simulation mode and to record data for comparison.

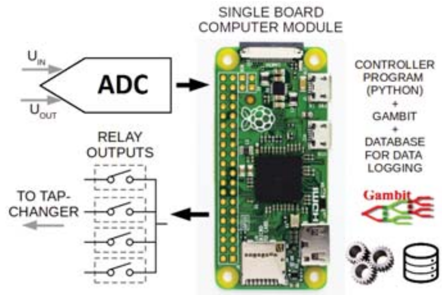

Fig. 8. Proposition of hardware implementation with single board computer

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