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Remedial Transactions Curtailment Via Optimization

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Abstract: The new method developed in this paper is aiming at transmission congestion management (CM). The new, Optimal Transactions Management method (OTM), is based on linear programming (LP), DC load flow (DCLF) and linear security constraints. The OTM method is embedded in Available Transfer Capabilities (ATCs) and Power Transfer Distribution Factors (PTDFs) definitions' environment. Well-suited for both preventive and corrective modes of operation, the OTM method aids transmission system operator in running a congested power system network, where congestions are due to transactions. Potential congestion threat is solved by finding the 'culprit' transaction and its optimal reduction. Besides the proposed downsizing of scheduled and/or committed transactions, controls of the OTM method also include redispatching of generation and load levels. The task is to establish a system state without constraint violations. To ensure the feasible network solution, both DC and AC power flows are used. The common 5 nodes/7 lines Ward&Hale sample power system is used to clarify the OTM method. Besides, six other power system networks including the real-life power system network of Serbia, Macedonia and Montenegro (part of the South East Europe – SEE grid) are used to test remedial potentials and cpu-time performances of the method. The 24-hour daily demand diagram is used with all test networks to study the effects of transactions as they are being superpimposed to the the regional grid. The remedial, transactions-curtailing OTM method is found well suited for market-related analyses precluding the hour-ahead, the day-ahead dispatch, as well as the real-time generation dispatch. It could also suit for the novel, Day Ahead Congestion Forecast (DACF) procedure used in power markets.

Keywords: Deregulation, Congestion management, Power markets, Optimal power flow.

1 Introduction

Nowdays, in real-time power systems operation, numerous power energy transactions exist in networks as a consequence of the closed deals on the market.

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According to the deregulation paradigm, no one should chalenge the customer's right to buy electrical energy from any indepent power energy supplier. Therefore, open access should be allowed without any restriction. As a consequence, energy trading and transactions through the high voltage power system network are multiplying.

Prior to deregulation, national utilities had interest to run and develop their own transmission networks, close tracking the load growth while planning the 'grids'. When the international energy market transactions claimed the open access right to the regional (national, ‘inner’) interconnected networks, this exposed many a network to higher line loading levels than planned. To maintain security, the transmission system operators (TSOs) were lawfully allowed to determine and perform all neccessary actions ‘to ensure that no violations of the various grid constraints occur’.

The actions in CM are usually redispatching of generation and load. With transaction playing a role as a common network participant, as well as a potential culprit of a cascading blackout, there is a serious but unspoken doubt whether to allow 'a guest' transaction to be a subject of control, or not?

1.1 Transaction – does it exist as a control variable, or not?

Bilateral transaction can be of two types, firm and non-firm. Firm transactions are not subject to curtailment and are willing to pay the congestion cost. Nonfirm transactions are unwilling to pay the congestion cost and are subject to curtailment. The curtailment is conveyed only in the study mode, prior to execution [1].

As far as (regional) network of Serbia and its TSO personell are concerned, all transactions are treated as firm transactions, in the above sense!

However, in this paper we advocate that under critical circumstances a minimal curtailment of the 'culprit' transaction should be allowed, even during the the time period when it is executed. This is a new for the region in question, but also, a novelty in general regarding the gathered intelligence. A culprit transaction is the one which causes the spotted congestion.

Free and uninterrupted transaction of goods (energy) is a synonym of the free trade. Nowdays, there is a directive that all deregulation project activities in Electric Power Sytsem of Serbia should converge towards the final application of coordinated auctions [2]. The 'dry run' period is already three years old. The deadline for the regional market to emerge is placed in the year 2015.

The changes in the power sector are big and serious. Therefore professional mind (in Serbia) assumes that the whole effect of deregulation would be lost if transactions are controlled in the inner network and otherwise to prescribed. Allegedly, whole CM problem will *a priori* be solved by implementing the so called coordinated auctions (for capacity) at the bordering tie-lines. The public dispute on this matter is lacking or is hushed at domestic conferences by numerous employees of the regulatory agency. The power system security of the regional network traversed by transactions will so entirely rely on the procedure of month-ahead and day-ahead auctioning of tie-line capacities. TSO has only the right to refuse transactions in the study mode, those which are bound to endanger security. Today, study mode implies the assumed or projected situation for the tie-line capacities on Wednesday of the third week in a month, applied throughout the month. The principle *use it or loose it* is assumed for the cross-border capacity. However, 'use them or loose them' provision for transmission rights is difficult to enforce in a timely manner [3].

The static security level of a power system is characterized by the presence or otherwise of emergency operating conditions (limit violations) in its actual (pre-contingency) or potential (post-contingency) operating states [4]. Prior to deregulation, MW interchange transaction was an active-power subproblem control variable [4]. The transaction in the new, deregulated, open-access environment should also legally and techically be made flexible to changes. Only if neccessary and as little as possible, and if and only if the steady state security of the system is threatened *due to this particular transaction*, i.e. *at least cost*.

Another 'failure to deliver' event similar to the transaction curtailment exists when already purchased generation in the day-ahead market is lost (due to outage, e.g.) prior to commitment. The lost generation is then purchased at the balancing market [3].

To our opinion, curtailing the minimum amount of the transaction causing the congestion deserves the same, *vis maior* treatment, like in the previous example, i.e. execution only in an emergency. Subsequently, the question of equity arises: only transaction causing congestion should be downsized, and only to the minimal extent. The whole procedure should be a routine, executed by the computer program and called in real-time if all other CM measures fail. These measures, if available, are security-based rescheduling of generation [1], of transactions [5] or, preferably, driven by market signals [6]. To our insight, there is no clear reference in the literature that transactions could be downsized. There is no clear reference to extraction of the so called culprit transaction. And, at last but not least, there is no reference that this operation could be coveyed actually during the execution of the culprit transaction, at least cost. These three points are the claimed novelities of this paper.

1.2 Transaction – from negotiation to blackout?

A Multi-agent negotiation model for security-related decission making is proposed in [7]. When the TSO (ISO) discovers high system overload risk, it immediately initiates negotiation with load agents. The negotiation issues include load curtailment by the load agent and compensating money offered by TSO. Agent than has to analyze the tradeoff between the compensation proposed by TSO and the expected monetary loss due to its load curtailment. This procedure seems potentially too time-consuming for the real time use, considering the transition speed between power system state security levels [4]. And on the other hand, baring in mind our inherent potential for endless negotiations, almost inaplicable. The evidence of numerous transactions-related blackouts in the world so far justify more radical measures at hand, just in case something goes wrong. The remedial OTM proposed in this paper seems to be appropriate for this purpose.

The transaction, i.e. the bilateral transaction, is an arranged delivery of electrical energy between the two independent grid participants, where one of them is buyer and another is seller. The multilateral transaction is an arranged delivery of electrical energy between two or more buyers and one seller, and *vice versa*. Mathematically, transaction is modeled as a pair of equal, sign opposite, real power injections of the power flow network model. The superposition principle of transactions to the base-case load flow makes it similar to the network switching model [8]. As the DCLF model became a regular tool within the open access paradigm, that implied expressing the transactions through the Power Transfer Distribution Factors (PTDFs), obtained by DCLF. Prior to deregulation, the more general term sensitivity factors was used [9].

With the new OTM method, the old, somewhat idealisticaly put criterion 'who is responsible for particular congestion and on which line', becomes operational. To aid this, the linear security constraints, Avaliable Transfer Capabilities (Avaliable Transmission Capacities, ATCs), are introduced per line instead of traditional line limits [10].

Congestion occurs whenever the system state of the grid is characterized by one or more violations of the physical, operational, or policy constraints under which the grid operates in the normal state or under any one of the contingency cases in a set of specified contingencies. Congestion is associated with a specified point in time (therefore, Serbian dry-run was a failure) and may arise in connection with power/energy markets on any time horizon [6].

Presenting the new OTM method for solving network congestions is the aim of the paper. The proposed method is tested on the predefined transaction schedule and computations of appropriate PTDFs and ATCs are carried out. This approach is developed in C++ on Windows^{TM} platform with assistance of the linear programming library procedure in Mathematica^{TM} 4.0 [11]. The results are verified via the Symbolic Analyzer of DC Load Flows, SADCLF [12] developed in Mathematica^{TM} 4.0 and the Power World^{TM} 12.0 educational version software package [13, 14].

2 Optimal Transaction Management Method

Computation of PTDFs and ATCs is the first step of the algorithm. Theoretically, if N_{node} is the number of nodes in the network, then the maximum number of possible transaction directions is

$$M_{trans}^{\max} = N_{node} \times (N_{node} - 1)\,. \tag{1}$$

Number of PTDFs is related to the number of transaction possible directions M_{trans}^{max} PTDFs depend on the grid topology and electrical position of the injection pair in the grid (positive for buyer and negative for seller). The DCLF is used for PTDFs evaluation on the ’empty grid’, i.e. the loadless network. The insight into the fully symbolical, analytical derivation of the Ward&Hale sample power system PTDFs, could be obtained from [12, 15].

The ATC is based on DCLF and PTDFs’ computations.

The ATC of a transmission system is a measure of unutilized capability of the system at a given time and depends on a number of factors such as system generation dispatch, system load level, load distribution in the network, network topology and the limits imposed on the transmission network.

The basic idea in the ATC calculations is: for a given set of system conditions to determine the maximum amount of power the transmission system can support, in addition to the already commited transmission services, when power is injected at one location and the same amount of power is extracted at the same time at another location without the violation of transmission constraints [1].

Being the line-oriented [13], the ATC is a part of the NTC (Net Transfer Capacity), computed for the whole network and every each pair of transaction end-nodes, according to base case load flow from the preceeding moment. Observed base case with the transactions becomes the new base case in the next time interval (an hour) and possibly, for a new transaction program, (2). When the ATC computation is completed for all transmission lines, ATCs are screened for the minimal value. The minimal ATC for the observed transaction, as an unique value for the network, is selected.

The ATC is positive (ATC^{+}), if the difference between the line thermal limit (apparent power) and the active power flow is positive, (3). Only then one could proceed with transaction additions, expecting no network congestion.

The (*N*-*k*)-steady state security checks of contingency analysis require appropriate PTDFs and therefore the ATCs also change, but the concept remains.

The ATC is negative (ATC^{-}), when the transmission line *ij* power flow is greater then the line thermal limit (Fig. 2). The negative *ATC*, i.e. ATC^{-}, pinpoints how many MW should be curtalied from the transaction by TSO to avoid network congestion. The Transmission Reliability Margin (*TRM*) is the MW margin introduced because of load flow data inaccuracies, control effects and errors, etc. For simplicity, in further analysis it would be assumed $TRM = 0$. Base-case is defined as the network power flow prior to transactions. One could easily view the line *i-j* active power flow as the result of superposition of the base-case power flow on the line observed, and a couple of active power margins, i.e.

$$P_{ij} = P_{ij}^0 + ATC^+ + TRM \ . \tag{2}$$

The common ATC definition (3) assumes the DCLF computed PTDFs, approximate (due to DCLF "inaccuracies", see [12] for fully in-hand matrix derrivation of the model) power flows and the line *i-j* thermal limit, as apparent power, i.e.

$$ATC = \begin{cases} \dfrac{S_{ij}^{tl} - P_{ij}}{PTDF}, & PTDF > 0 \\ \infty, & PTDF = 0 \\ \dfrac{-S_{ij}^{tl} - P_{ij}}{PTDF}, & PTDF < 0 \end{cases} \tag{3}$$

$$\left|PTDF\right| \le 1 \ . \tag{4}$$

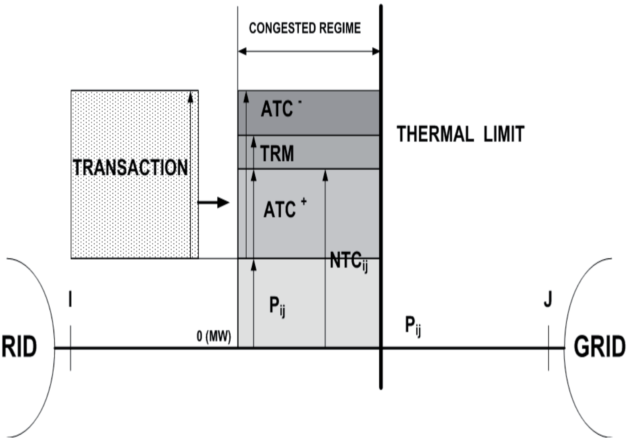

Fig. 1 – *Line i-j: the transaction component active power flow superposition to the base case.*

Since DCLF computations, in spite of the DCLF „drawbacks“ ([12]) cannot be omitted from the PTDF computations, albeit, they are crucial to the “ATC-PTDF paradigm”, something else could be done to bring about some realism to our observations. Here, we introduced the ACLF calculated reactive line power flows obtaining somewhat more realistic ATC (lower) values which contributed to the security side. As in Fig. 2, the transmission line *i-j* thermal limit apparent power is „corrected“ for reactive power, (5). One ATC value per line is assumed.

$$ATC = \begin{cases} \dfrac{\sqrt{(S_{ij}^{tl})^2 - (Q_{ij})^2} - P_{ij}}{PTDF}, & PTDF > 0 \\ \infty, & PTDF = 0 \\ \dfrac{-\sqrt{(S_{ij}^{tl})^2 - (Q_{ij})^2} - P_{ij}}{PTDF}, & PTDF < 0, \end{cases} \tag{5}$$

$$|PTDF| \le 1\,. \tag{6}$$

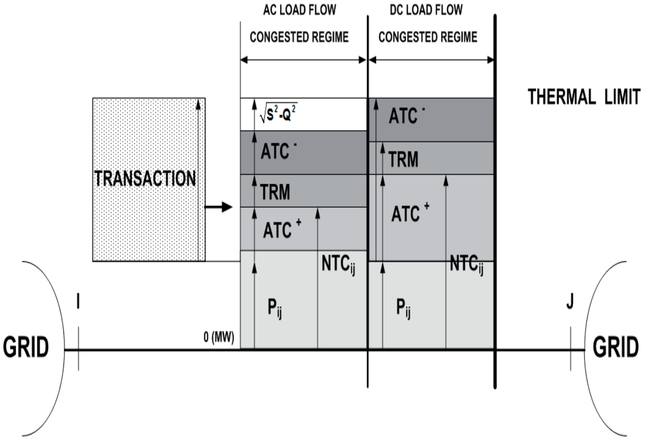

Fig. 2 – *Line i-j*: *comparison of solutions between the* DC *and the* AC *load flows*.

The proposed linear security-constrained Optimal Transactions Management method (OTM) is based on linear programming, DCLF, ATCs and PTDFs. Correcting the transaction dispatch with OTM is concurrent with correcting the generation dispatch by linear programming [9]. Here, in this paper, the metod of Wood and Wollenberg is upgraded in such a way that ATC values (nowadays published by/for TSOs) are used insead of classical line limits and corrective generator “shifts” here connote the transaction in/out injection pairs instead of only generator injection powers, as with the Wood and Wollenberg renown method [9]. Therefore, it would be very easy if one wishes to repeat these calculations.

Since we wish to correct for transmission overloads, we will try to do so with the minimum deviation from the transactions dispatch schedule.

The linear programming variables are the *i*-th transaction DP_i, corrective increments DP_i^+ and decrements DP_i^- (all values positive):

$$DP_i = DP_i^+ - DP_i^- . \tag{7}$$

The objective is to minimize the sum of shifts from the given schedule

$$\textbf{Minimize} \ \ \sum_{i=1}^{n}(KDP_i^+ + KDP_i^-), \tag{8}$$

subject to

$$\sum_{i=2}^{N} P_i + \sum_{i=1}^{n}(DP_i^+ - DP_i^-) = 0, \tag{9}$$

which is the Tellegen’s theorem (conservation of power for the lossless network) where P_i is the active power injection (generator/load).

The PTDF values for particular lines and transactions are expressed here as a_{li}, where *l* is the observed line and *i* is the scheduled transaction.

$$\begin{aligned} &\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{li}\left(\mathrm{DP}_{\mathrm{i}}^{+} - \mathrm{DP}_{\mathrm{i}}^{-}\right) \le ATC_l^{+} \\ &\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{li}\left(\mathrm{DP}_{\mathrm{i}}^{+} - \mathrm{DP}_{\mathrm{i}}^{-}\right) \ge ATC_l^{-} \end{aligned} \tag{10}$$

$$\begin{aligned} &0 \le DP_i^+ \le P_i^{\max} - P_i^0 = ATC_l^+ \\ &0 \le DP_i^- \le P_i^0 - P_i^{\min} = ATC_l^- . \end{aligned} \tag{11}$$

The a_{li} value adapts to changes of network topology in respect to the case study. If applied to post-contingency corrective control, then these values should be dully recalculated. This procedure is fully automated. Some comparative results for different networks are presented in sequel.

3 Numerical Example

Nowadays, many TSOs are using ‘preventing’ CM methods for DACF. Explicit and implicit auctions, coordinated auctions, market splitting, pro-rata and first come-first served methods are known. Their transactions scheduling is based on the DCLF computation, neglecting for the computational reasons the real constraints of the grid, such as reactive power and complex nodal voltages. The simplified approach has inherent disadvantages because the reactive power additionaly decreases the ATC values and distorts the line loading pattern created by transactions superpimposed to the base case.

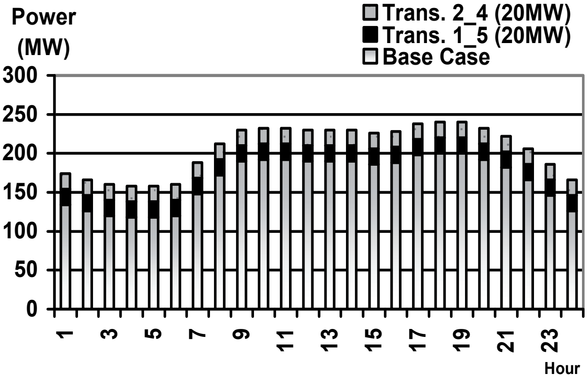

Fig. 3 – DACF *for transactions* 1-5 *and* 2-4.

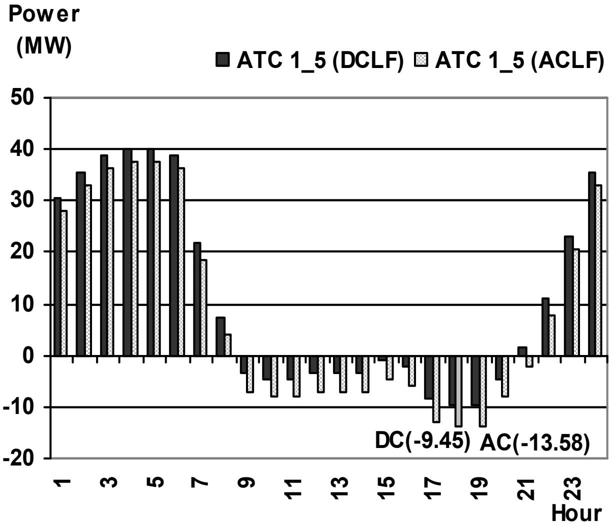

Fig. 4 – DACF: *Comparison of the ATCs* (*transaction* 1-5) *for the DCLF and the ACLF definitions.*

The new OTM method uses similar approach, but the main difference in comparison with other methods is the LP-based remedial rescheduling (curtailing) of transactions.

The OTM method features the downsizing of only those transactions causing congestions, and only to the minimal extent.

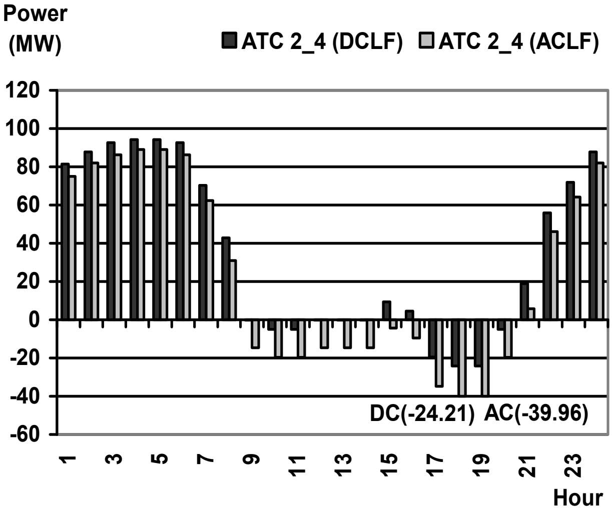

Fig. 5. – DACF: *Comparison of the ATCs* (*transaction* 2-4) *for the DCLF and the ACLF definitions*.

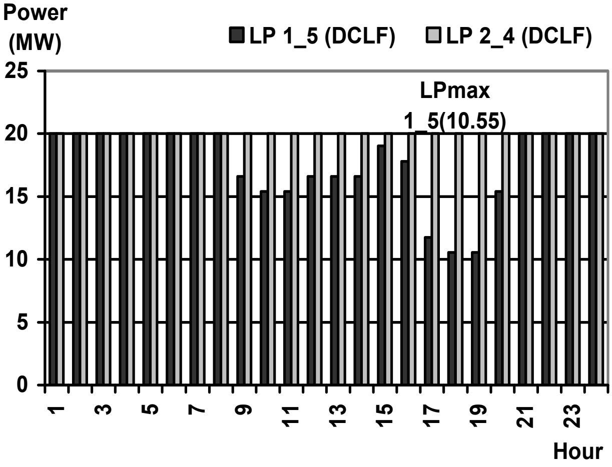

Fig. 6 – DACF: *the OTM for transactions* 1-5 *and* 2-4 for *the DCLF definition*.

The computer program embedding this procedure in real-time, performs transactions curtailing even if all other measures fail (e.g. generation rescheduling also performed by the same program). This means that the new OTM method could complement the 'preventing' CM methods when it comes to operation. Another fact is that all previously mentioned methods are based on the DCLF, while the OTM incorporates both some ACLF and DCLF features, minimizing masking effects.

The OTM approach is verified on the 5 nodes/7 lines Ward&Hale sample power system. The schedule assumes transactions between nodes (1 and 5) and (2 and 4) retaining their level throughout the day. The daily demand diagram variations (Fig. 3) produced congestions on lines 1-2 and 2-5, during the period from 9 am to 9 pm. All these different congestion scenarios are successfully solved by the OTM method which determines that transaction 1-5 is responsible for causing network insecurity. The same approach is used with the ACLF. One could notice that reactive power occupied transmission lines capacity and reduced the ATCs at ACLF in comparison with DCLF, where $\mathrm{ATC}^{\mathrm{AC}}_{\mathrm{Trans.1\text{-}5}}<\mathrm{ATC}^{\mathrm{DC}}_{\mathrm{Trans.1\text{-}5}}$ and $\mathrm{ATC}^{\mathrm{AC}}_{\mathrm{Trans.2\text{-}4}}<\mathrm{ATC}^{\mathrm{DC}}_{\mathrm{Trans.2\text{-}4}}$ (Figs. 4-7, 11). The most critical scenarios resulting in curtailing 1-5 and show in both DCLF and ACLF, at 6 pm and 7 pm (Figs. 8-12).

The DACF described was used with six other grids (**Table 1**) with the different number (from 1 to 4) of hourly transactions (Fig. 13), and changing the daily demand diagram (Fig. 14).

The idea was to investigate the influence of grid dimensionality to the computational efforts (CPU time). The grids were tested at one single PC unit with 2.8GHz, 64 bit processor and 512MB RAM memory.

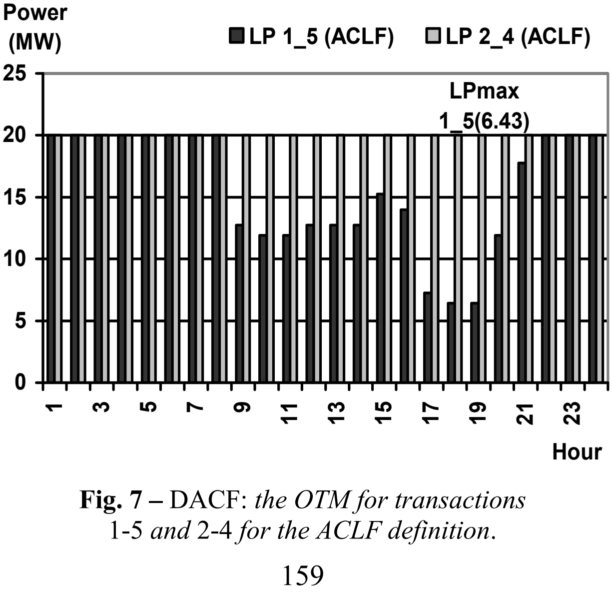

Fig. 7 – DACF: *the OTM for transactions* 1-5 *and* 2-4 *for the ACLF definition.*

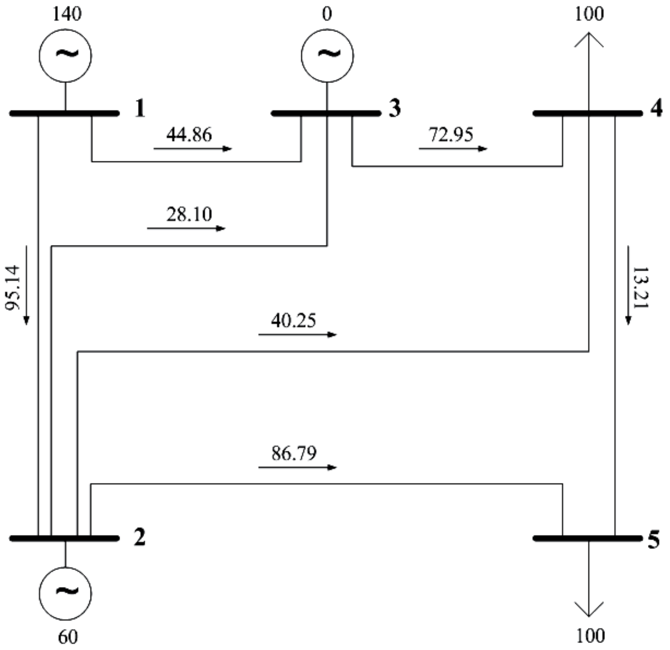

Fig. 8 – *Ward&Hale test system, base case at* 6 pm *and* 7 pm.

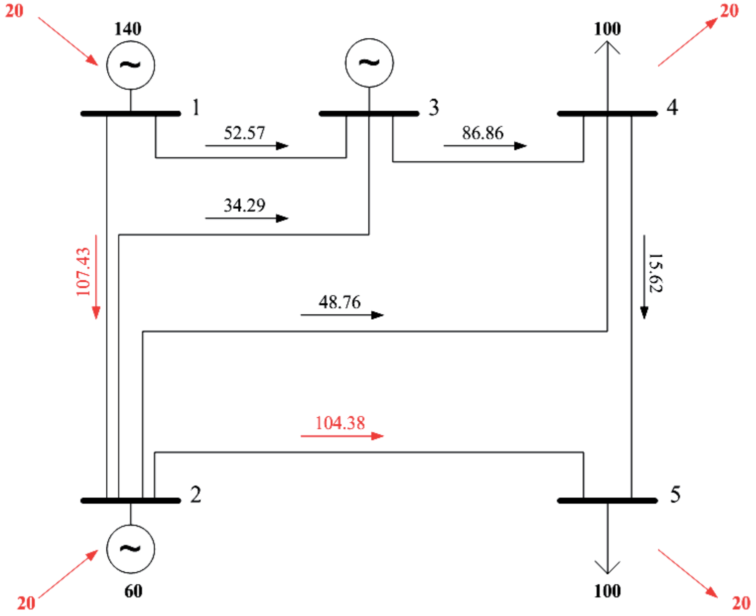

Fig. 9 – *Ward&Hale test system, with transactions* 1-5 *and* 2-4 *causing congestion at* 6pm *and* 7pm.

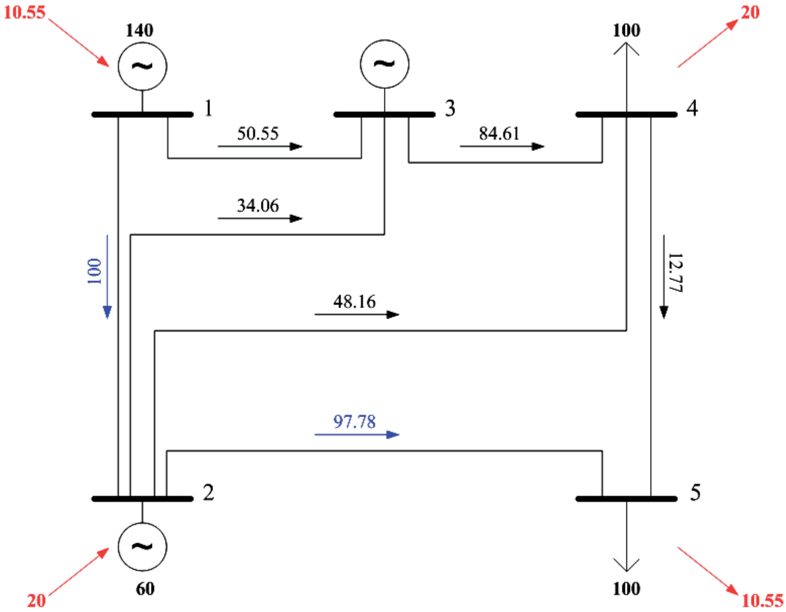

Fig. 10 – *Ward&Hale test system, with transactions* 1-5 (*curtailed*) *and* 2-4 , *after CM by the OTM, at* 6 pm *and* 7 pm.

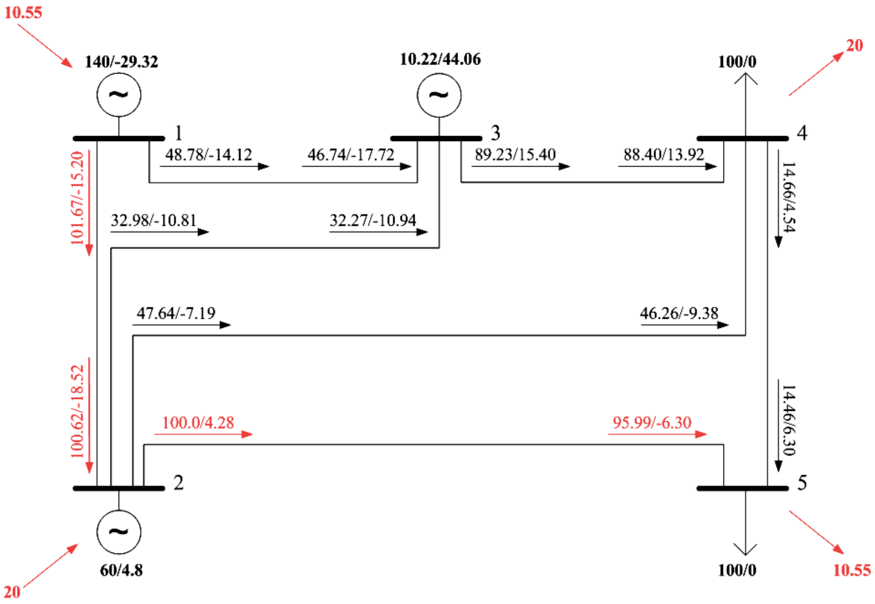

Fig. 11 – *Ward&Hale test system, transactions* 1-5 (*curtailed, congestion masked*) *and* 2-4, *after CM by the OTM, ACLF, at* 6pm *and* 7pm.

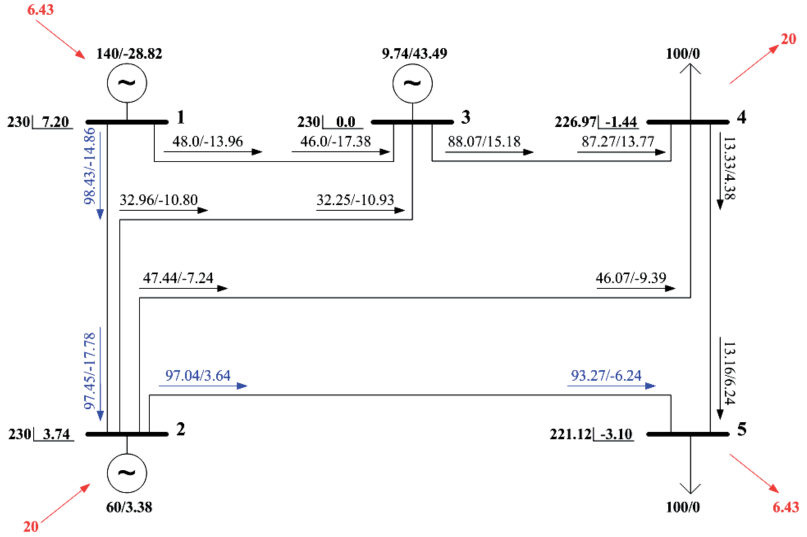

Fig. 12 – *Ward&Hale test system, transactions* 1-5 (*curtailed further*) *and* 2-4 , *after CM by the OTM, ACLF, at* 6 pm *and* 7 pm.

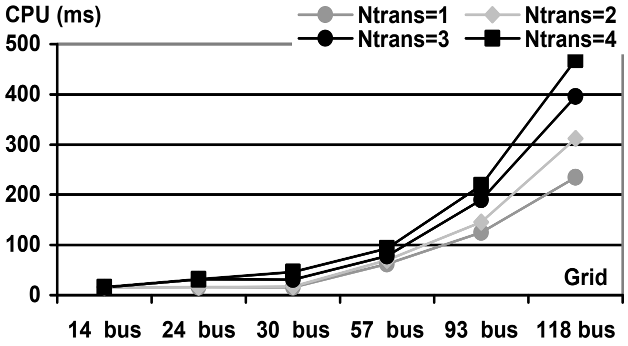

Fig. 13 – *Comparison of CPU times for the PTDF, ATC and DCLF computations,* 1 *hour, for* 1 *to* 4 *transactions.*

Table 1
Tested power systems in order of their dimensionality.

Grid	Buses	Lines
IEEE	14	20
IEEE (RTS)	24	34
IEEE	30	41
IEEE	57	80
Serbia, Montenegro, Macedonia	93	115
IEEE	118	186

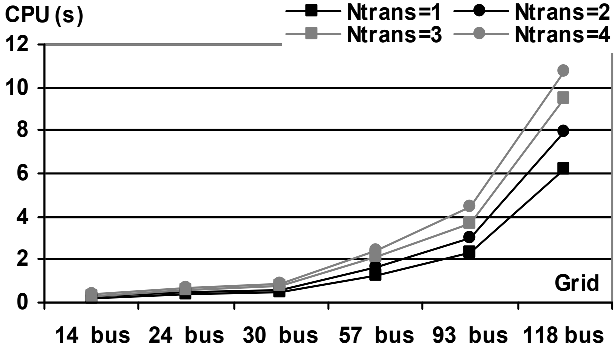

Fig. 14 – DACF: *Comparison of CPU times, the PTDF, ATC and DCLF computations,* 24 *hours,* 1 *to* 4 *transactions*.

The results show that CPU times for the PTDF, ATC and DCLF computations have the quadratic dependence regarding the number of the network nodes.

This fact assessment is important for the grid model building in market modeling. Sometimes it could be necessary to decide whether to make simple equivalents of external systems or grid areas in order to reduce computing PTDFs and ATCs for the scheduled transactions. This approach could help in decreasing the computational effort and pays off especially for the large power networks.

4 Conclusion

In this paper, the new remedial Optimal Transaction Management (OTM) method is shown. The OTM method proposes the LP-based remedial curtailing of (only) ‘culprit’ transactions, as a tool for solving congestion problems in a multi-transaction network. The algorithm is clarified on the 5 node/7 lines Ward&Hale sample power system, used for explanatory purposes. Case studies are performed on six other real-life as well as test power system networks, varying number of transactions.

The new OTM algorithm is embedded in contemporary definitions of DCLF, PTDF, ATC and DACF. Security constrained optimization function of the OTM targets potential ‘grid’ congestion. The main idea of the method is to allocate, reschedule and/or downsize only the 'culprit' transaction, the one directly causing congestion, and only to the minimal extent.

Superposition principle and the DACF are aiding this solution. The algorithm suits well for the real-time use. It performs transactions curtailment in addition to traditional generation rescheduling.

In some regions in “transition”, like Serbia, power systems incentives in deregulation are lacking the broad public dispute (more important political issues at stake!). This paper “dares to propose” that CM security controls of the regional network should optionally include remedial, minimal downsizing of the scheduled and/or committed ‘culprit’ transactions. This control is not even considered as an option when it comes to discuss the topic with the involved professionals during domestic conferences, like the CIGRE regional Serbian conference, for example.

The new OTM method is indicated for both preventive and corrective grid operation modes. The CM actions are commonly the redispatch of generation and load levels in order to establish a system state without constraint violations. The new remedial OTM method is well suited for market-related analyses precluding the hour-ahead, the day-ahead dispatch, but especially for the real-time generation dispatch, which was shown in the paper by executing the computer program based on the new remedial OTM method on seven networks.

Feasible network solutions are obtained and the so-called masking effects (the DC load flow “errors”) are successfully minimized by combining the DC and the AC power flow definitions of the ATC. CPU times for the OTM computations regarding DCLF, PTDF, ATC and DACF, approve the OTM method engagement in CM long-term, operation planning and immediate (on-line) remedial tasks, for any time horizon involved.

5 List of Symbols and Abbreviations

5.1 Symbols

N_{node} – number of nodes in the network

M_{trans}^{max} – maximum number of possible transaction directions in the network

P_{ij} – line *i-j* active power flow (MW)

Q_{ij} – line *i-j* reactive power flow (MVAr)

P_{ij}^{0} – line *i-j* active power flow in the base-case (MW)

S_{ij}^{tl} – line *i-j* thermal limit, apparent power (MVA)

P_i – active power injection (generator/load)

N – total number of network nodes, slack node is numbered 1

n – total number of transactions

K – constant in the LP-problem formulation, any large number

DP_i – transaction corrective increment in LP-problem formulation

DP_i^{+} – transaction corrective increment upwards, positive value

DP_i^- – transaction corrective increment downwards, positive value

a_{li} – PTDF value, for *l* - the observed line, and *i* - the scheduled transaction

P_i^0 – bus *i* base-case active power injection

P_i^{max}, p_i^{min} – bus *i* upper and lower active power limits, respectively

5.2 Abbreviations

CM	Congestion Management (method)
OTM	Optimal Transactions Management (method)
LP	Linear Programming (method)
DCLF	Direct Current Load Flow (method)
ACLF	Alternating Current Load Flow (method)
ATC	Available Transfer (Transmission) Capability (Capacity)
ATC^+	Available Transfer Capacity, positive value
ATC^-	Available Transfer Capacity, negative value
$\mathrm{ATC}_{\mathrm{Trans}\,k-l}^{\mathrm{AC}}$	Available Transfer Capacity, evaluated by ACLF, for transaction between *k* and *l* nodes
$\mathrm{ATC}_{\mathrm{Trans}\,k-l}^{\mathrm{DC}}$	Available Transfer Capacity, evaluated by DCLF, for transaction between *k* and *l* nodes
NTC	Net Transfer Capacity
TRM	Transmission Reliability Margin
PTDF	Power Transfer Distribution Factor(s)
DACF	Day Ahead Congestion Forecast
SEE	South East Europe
TSO	Transmission System Operator
ISO	Independent System Operator
C++	a high level programming language
SADCLF	Symbolic Analysis of DC Load Flow (computer program)

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