SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 4, No. 2, November 2007, 189-206

Congestion Management Utilizing Concentric Relaxation

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Abstract: In the market-oriented power system environment, congestion management is a novel term connoting the power system steady state security functions. A large number of transmission transactions are dispatched in the regional day-ahead market and traverse the network adding to the power flow loading of the grid elements. Congestion is defined as a network security limit violation prospective due to transactions. Congestion management is a set of measures aimed at solving the congestion problem. This paper devises the concentric relaxation assisted approach to open access transmission network congestion management. The DC load flow symbolic simulator generates line power transfer functions. Congestion management is a systematic procedure based on linear programming. The DC load flow symbolic simulator generates all constraints and the black-box optimization library function is used to solve the problem of congestion on a sample IEEE RTS power system.

Keywords: Congestion management, DC load flow, Concentric relaxation, Open access, Visualization.

1 Introduction

The power system network open transmission access task is to "impartially provide transmission services to all buyers and sellers". The "extent of use" of transmission resources becomes the matter of primary importance, which will allegedly, in the long run transform the paradigms of system control. Commonly, the new open rules for transmission access concern above all the network, and then the generators. In power generation, application of economic rules was always taken for granted. The generator production costs have always comprised a component commensurate with the value of investments over the project lifetime period (capital costs), and the component consisting of the sum of fixed and variable costs for running the plant. The power system high voltage transmission network is usually built and operated as a public project with costs incurred by the government to the benefit of the people.

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Nowadays, in the liberalized and unbundled system transmission and generation, planning to run or build the power system network would require determining "who is responsible for the transaction and through which line". The fee for these services is unbundled from the other power system costs, separately determined and pinned to the generation costs. The common carrier role for transmission brought about by open access results in very different uses of the transmission system than those for which it was planned and designed. The independent system operator (ISO) is responsible for determining the necessary actions to ensure that no limit violations of the various grid constraints occur. It is this comprehensive set of actions that one refers as congestion management.

The DC load flow is a linear approximation to the nonlinear load flow problem, producing an approximate megawatt flow solution. Its advantage is of being extremely fast. Its accuracy against the "true" AC load flow is occasionally verified. In contingency analysis it is often used for variants screening, while the AC load flow must be used for greater accuracy, to confirm or reject a potential solution. The full matrix derivation of the DC load flow method is offered in [1]. The DC load flow is transferred into the symbolic analysis environment stressing the benefit of applying the symbolic approach.

In this paper, bilateral transactions (“agents”) come out as closed -form expressions – linear combinations of network transfer functions, featuring susceptances in the closed form of so called Power Transfer Distribution Factors (PTDFs) and power injections. The generated form of transactions as symbolic transfer functions enables easy handling of agents and the problem naturally proceeds as the linear programming optimization with generation/load minimal curtailment in congestion management, with transactions used as system variables. The coded transfer functions are completely generated by the symbolic-oriented computer program SADCLF prior to optimization [2]. Therefore, the environment for symbolically assisted numeric computations is enabled in a systematic way. Multilateral transactions are defined and obtained as linear combinations of bilateral transactions. The proposed method is a novel symbolically-assisted approach to the problem of transactions identification and transactions management under stressed and normal conditions.

Service identification and congestion management are important functions of the ISO in a deregulated environment. Various approaches have been reported in the literature. In the open electricity market the transaction is a bilateral exchange of power between the buyer and the seller [3]. The bilateral transmission capacity (BTC) is defined as the maximum real power, incremental above a given operating point, that can be securely received at bus i from bus j [4]. The more used term nowadays is the available transfer capability or the available transmission capacity (ATC) which is not restrained on bilateral exchange, with quite a few papers on this topic. On the other hand, congestion in a transmission grid “occurs due to an operating condition that causes limit violations on one or more ‘flowgates’ in the system” [5]. The congestion relief in a bilateral transaction environment is addressed in this paper by using the LP-based procedure and DC load flow transfer functions generated by the DC power flow symbolic simulator. The method is based on the minimal redispatch of transactions and disregarding the economic value of the transaction adjustment. It could be easily upgraded to include some of the “usage based” methods [6], as the second step of a two step procedure, where the total congestion cost is first allocated to the congested components, and then to the transactions that use these components. The congestion generates revenue which could be paid back to the transmission users (Norway) or paid-off to the holders of transmission congestion contracts (California) [7]. The objective function used in [8] is the overall profit of all market participants which is maximized. It considers the overall profit of all participants, although this information is naturally hidden. The method proposed here assumes that what an ISO could at most do is “to do as little harm as possible” by advising the transacting parties to curtail (the minimum of) their load. Therefore, the identification of the minimal curtailed overall transacting load seems an appropriate objective. Various congestion management schemes for different restructuring paradigms have appeared in the literature. A relevant brief overview appeared lately in [9]. The method is also embedded in the bilateral/multilateral transactions environment, prone to usage-based schemes (a counterweight to nodal-pricing schemes, based on [10]). The Tao and Gross method like the method proposed in this paper, makes full use of the DC load flow method and the LP-guided procedure to remove the overload congestion attributed to each transaction from the network in the most economic manner. The congestion relief objective of [9] is rather sophisticated: to maximize the value of the limited transfer capability measured by the offers. The method [9] also inherits the notions of “dominant flows”, “counter flows”, to describe the components of the line flow contents attributed to bilateral transactions (“agents”), as known from [6], relying on the numerical rather than symbolically oriented computation that is proposed in this paper. The benefits of symbolically oriented computation are elaborated in sequel, for more elaborate explanation relating the load flow application, see [1, 2].

2 Symbolic Transfer Functions

Symbolically oriented bilateral/multilateral transactions analysis is in the scope of this paper. There is an inherent advantage in using symbolical rather than numerical analysis in transaction allocation procedure [1, 2]. To clarify this, it should be recalled that the traditional, numerical approach favors a number as an object. Results are given in the form of the tables of numbers. To change a single parameter value (injection, network topology) means to undergo repeating the complete analysis. However, symbolic approach has a numerical computation as a consequence (subset) of the symbolic calculations. Symbolic approach is used to assist numeric computations for power system software development.

Numerous load flow executions produced are actually calculations for topologies differing from the network base case by only one element (e.g. contingency analysis, network switching, expansion planning). These calculations are prone for symbolic analysis. The solution is to start with the electrical network of the most general topology. Electrical network symbolic simulator SADCLF (Symbolic Analysis of the DC Load Flow) is an upgraded version of computer program [1] in *Mathematica* [11]. SADCLF is automatically generating the network symbolic response, i.e. the line DC load flow transfer functions in the required partial or full symbolic form. The extent of how many symbols to use is coordinated thusly: all power injections are always fully symbolic and susceptances maintained symbolic for those branches to be switched on/off, otherwise numeric.

After obtaining transfer functions for the most general network topology, different analyses (sensitivity, quantitative, qualitative) could be performed. The slack-node (function), which could easily be attached to any node, without reordering or renumbering, is one of the features of the SADCLF simulator. This feature is mostly plausible for analyses requiring the abundant recalculation of distribution factors, as for the nodal-pricing schemes [10]. The same feature makes the symbolically-oriented DC analyzer suitable for assessing the tricky congestion situations due to contingencies [9]. However, to present this feature is out of the scope of this paper.

The optimization linear programming procedure based on the generation/load curtailment involving bilateral and multilateral power transactions is developed in sequel of this paper. The code generated by SADCLF is combined with the black-box *Mathematica* optimization library. One of the chief simplifications made in this paper is the representation of all the transmission (line/transformer) and generation constraints (limits) in terms of transactions.

3 Congestion Management

A. *Security Assessment under Transactions*

Security assessment, traditionally, has two functions. The first is violation detection in the actual system operating state. It entails monitoring actual flows, voltages, etc., and comparing them against prespecified limits. The second, more demanding factor of security assessment is contingency analysis. It is performed on a list of "credible" contingency cases (single/multiple component outages). If they occurred, those contingencies would create steady-state limit violations (l.vs.), emergencies sometimes resulting in cascade network deterioration and, possibly, in a blackout. The power system operator (or an automated security function) can respond to each insecure contingency case by: a) altering the pre-contingency system operating state to mitigate or eliminate the emergency; b) developing a control strategy that will alleviate the emergency, or c) deciding to do nothing, assuming that the post-contingency emergency is small or unlikely. In the open access mode of operation, transmission and generation are no longer owned and controlled by the same entity. The Independent System Operator (ISO) is responsible for maintaining system security, but is not completely free to operate and self-schedule all generation resources to meet its needs. To provide an adequate regulation service for primary regulation, ISO may run some generation facilities on its own, or may arrange contracts with generation companies to hold generation capacity.

Steady-state security (contingency) analysis and the novel transmission access congestion management are related through the traditional concept of network component (line/transformer) limit violations. Congestion in a transmission grid occurs due to an operating condition that causes limit violations on one or more components in the system network. In a price based congestion management, ISO is allowed to take an active role in managing congestion by redispatching resources based on bids received from the market participants. The role comprises such procedures as avoiding congestion in advance, and asking the transacting parties to curtail their transactions. Since the congestion generates revenue, this revenue can be distributed back to the transmission users or paid-off to the holders of transmission congestion contracts. One of the tasks before the allocation (usage based) methods is to send the correct "price signals" for the congestion and thus "equitably" allocate the congestion relief costs to transactions.

Congestion occurs whenever there is one or more l.vs. of the physical, operational or policy constraints under which the grid operates in the normal state or under any of the contingency cases in a set of specified contingencies. Congestion is associated with a specified point in time and it may arise during the day-ahead dispatch, in the day-ahead market, the hour-ahead dispatch, in the hour-ahead market or the real-time operations of the system, in the balancing market [12].

In the sequel of this paper, the optimization-based procedure will be described in which ISO will be granted the right to administer a minimal number of transactions in such a way, as to relieve the congestion in the network. The optimization procedure is based on traditional generation dispatch method using linear programming, the security-constrained OPF [13]. As a novelty, it involves bilateral power transactions as independent system variables in a symbolically guided procedure.

B. *Optimization procedure*

The congestion management procedure developed in this paper takes an advantage of the well-organized and systematic approach to correct the generation dispatch for overloads using sensitivity methods. To correct one overload often means to cause another somewhere else in the network, unless a systematic approach is applied. A proposed method is a linear programming (LP) based procedure set up to minimize the amount of transaction curtailing. Assuming that prior to corrections, equilibrium exists in the network (base case) in which all line flows are algebraic sums of transactions. At least one of line constraints is violated.

The objective is to minimize the sum of transaction changes subject to line flow constraints and generation shift limits. The LP algorithms require that all variables be positive. Since transactions could either ascend or descend, we introduce

$$DP_i = DP_i^+ - DP_i^- , \tag{1}$$

where DP_i^+, DP_i^- stand for the *i*-th (of *n*) transaction or agent-flow DP_i upward and downward “shifts”, respectively.

The final expressions for the LP are

Minimize:

$$\sum_{i=1}^{n} (K\,DP_i^+ + K\,DP_i^-) , \tag{2}$$

where the value of *K* can be chosen as any large number [13].

Subject to

$$\sum_{i=1}^{n} P_i + \sum_{i=1}^{n} (DP_i^+ - DP_i^-) = 0 \tag{3}$$

representing the Tellegen’s theorem [1], with all network injections (generation, load, traqnsaction injection-pairs), and

$$\begin{aligned} &\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{li}\left(DP_{\mathrm{i}}^{+} - DP_{\mathrm{i}}^{-}\right) \le f_{\mathrm{l}}^{\max} - f_{\mathrm{l}}^{0} \\ &\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{li}\left(DP_{\mathrm{i}}^{+} - DP_{\mathrm{i}}^{-}\right) \ge -f_{\mathrm{l}}^{\max} - f_{\mathrm{l}}^{0} \end{aligned} \tag{4}$$

representing line flow constraint, where $f_l^{\max}$ is a line maximum flow and f_l^0 is a base case flow on line, a_{li} is a symbolic expression containing line transmittances derived by SADCLF [1,2] for the line *l* end nodes, i.e. a PTDF, and

$$\begin{aligned} 0 \le DP_i^+ &\le P_j^{\max} - P_j^0 \\ 0 \le DP_i^- &\le P_j^0 - P_j^{\min} \end{aligned} \tag{5}$$

for generator shift limits; P_j^0 is *j*-th bus generation and $P_j^{\max}$, $P_j^{\min}$ stand for generator limits, *i=1,...,n, j=1,...,N, l=1,...,b; n* is number of transactions, *N* is number of nodes, b is number of branches, respectively.

The load flow on line could be completely formed from transactions, e.g. on line *l*

$$\sum_{i=1}^{n} a_{li}(DP_i^+ - DP_i^-) \tag{6}$$

or transactions could be superimposed to base case flow f_l on the line.

The objective is to correct for transmission overloads with the minimum deviation to transactions. The other important ISO objective is to detect which of transacting parties should change their transactions and to study the "tier effect" (in circles) of congestion management actions propagation throughout the network.

The idea is one of the concentric relaxation methods [14] and seems worthwhile for visualization purposes. Concentric relaxation makes use of the fact that effects of changes in network are propagating through the network in concentric circles (“tiers”, [14]), from the position in the network where the changes occurred, outwards.

SADCLF is used to generate the line agent-flow based transfer functions. Base case load flow founded on transactions is evaluated and l.vs. detected. The code generated by SADCLF is combined with the black-box optimization library `ConstrainedMin` *Mathematica* function. This function allows specifying an objective function to maximize or minimize, together with the set of linear constraints or variables. After finding the optimal solution, transactions are adjusted for the new distribution.

4 Numerical example

Consider the well known IEEE Reliability Test System (RTS) of 24 nodes and 34 branches.

Assume the transactions comprising nodes 8, 9, 15 and 23 (Fig. 1). Let their values be $P_{15,8}$ = 61 MW, $P_{15,9}$ = 50 MW, $P_{23,8}$ = 110 MW, $P_{23,9}$ = 125 MW. The example assumes the line limits set at 220 MW. The l.vs. were detected on lines 11-14 and 16-19. The LP-based procedure (2) – (5) gave

$$DP_{158}^+ = DP_{159}^+ = DP_{238}^+ = DP_{239}^+ = 0 \tag{7}$$

and

$$DP_{158}^{-} = 40MW, DP_{159}^{-} = 40MW, DP_{238}^{-} = 15.721MW, DP_{238}^{-} = 0 \tag{8}$$

The evaluated minimal sum of weighted transaction changes (2), was $C = 95.721\,\text{MW}$.

Assisted by the LP-based procedure, the ISO role should be to ask the transacting parties at buses 15 and 23 (power plants) and 8 and 9 (consumers) to curtail at the same time the determined amount of their loads. This action should automatically reduce the load of the determined agents identified as responsible for congestion on transmission lines 11-14 and 16-19, Fig. 2.

To recapture the loading conditions prior to optimization, the ISO should be free to activate the alternative contracts or the contracts with the generation companies holding their capacities in reserve for such critical situations [12]. The whole procedure should be repeated in case that the new l.vs occur in the network after the new transaction load flow pattern has been established.

In the deregulated systems it has been recognized that ISOs are under increased scrutiny since their decissions (to partially curtail transactions or not) can have tremendous financial impact on market participants. Practical answers are needed quickly. The power systems in transition are looking up at deregulated systems for ready answers. Tradittional load flow has never offered abundancy in comprehendable information, untill visualization as a concept was offered as a solution.

Visualization supports the LP-based congestion management symbolically assisted approach. The idea is that an operator should check the optimization results and reply that he is better off by just using the graphs. The transaction, decreased or increased in magnitude, spreads this change proportionally throughout the network on all agent-flows belonging to that transaction, Figs. 3-12. The constant of proportionality is the sum of driving-point transmittances derived by SADCLF. But the significance of change in flows that occurred is judged by man.

The "concentric relaxation" point of view puts the line with l.v. each time into the center and enables the decision which of the counter-flows should be manipulated in order to decrease the net flow in the congested line.

By this procedure, all that the operator needs is *to see the effects of his actions* and to assess the secure state of the system. In that sense the analyzer concept has the power of giving the immediate insight into the network flows, like the old network “wired” analyzers of the early fifties, prior to numerical load flow calculations. It also assumes closer man-“machine” interaction and livelier and more loose manual operation.

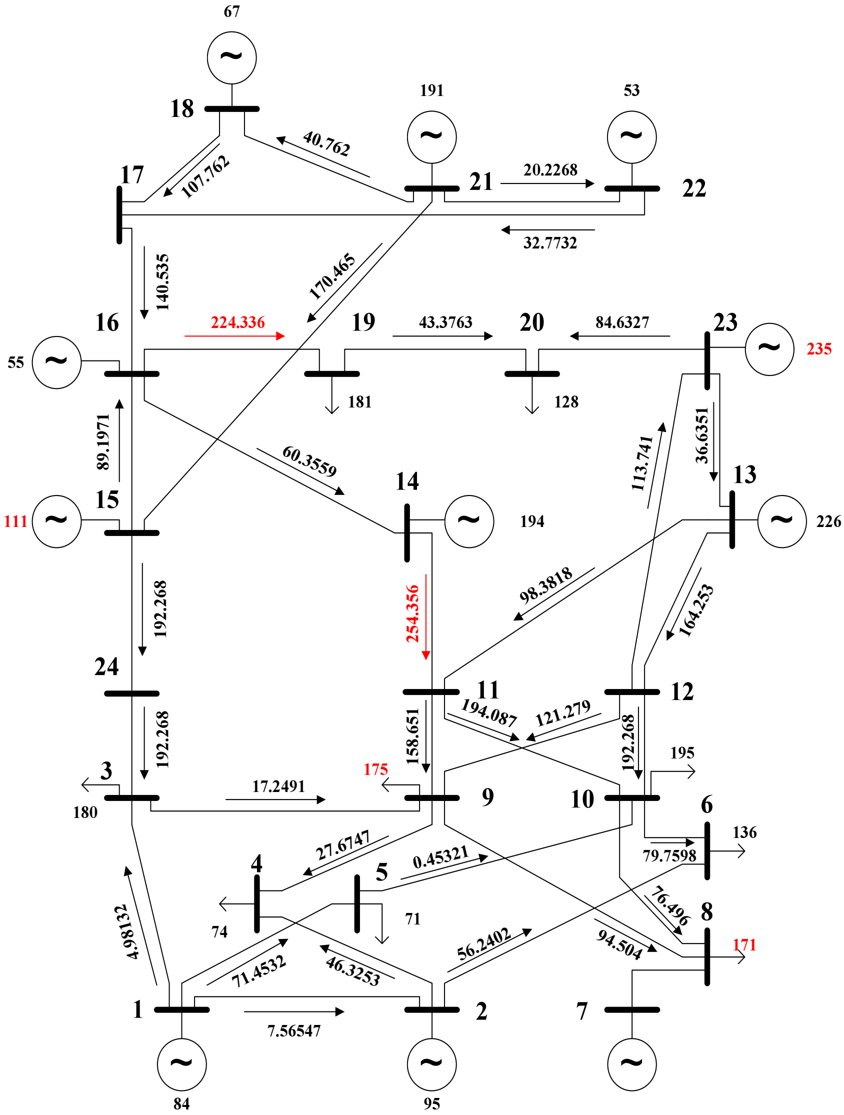

Fig. 1 – IEEE-RTS *network: congested lines* 11-14 *and* 16-19.

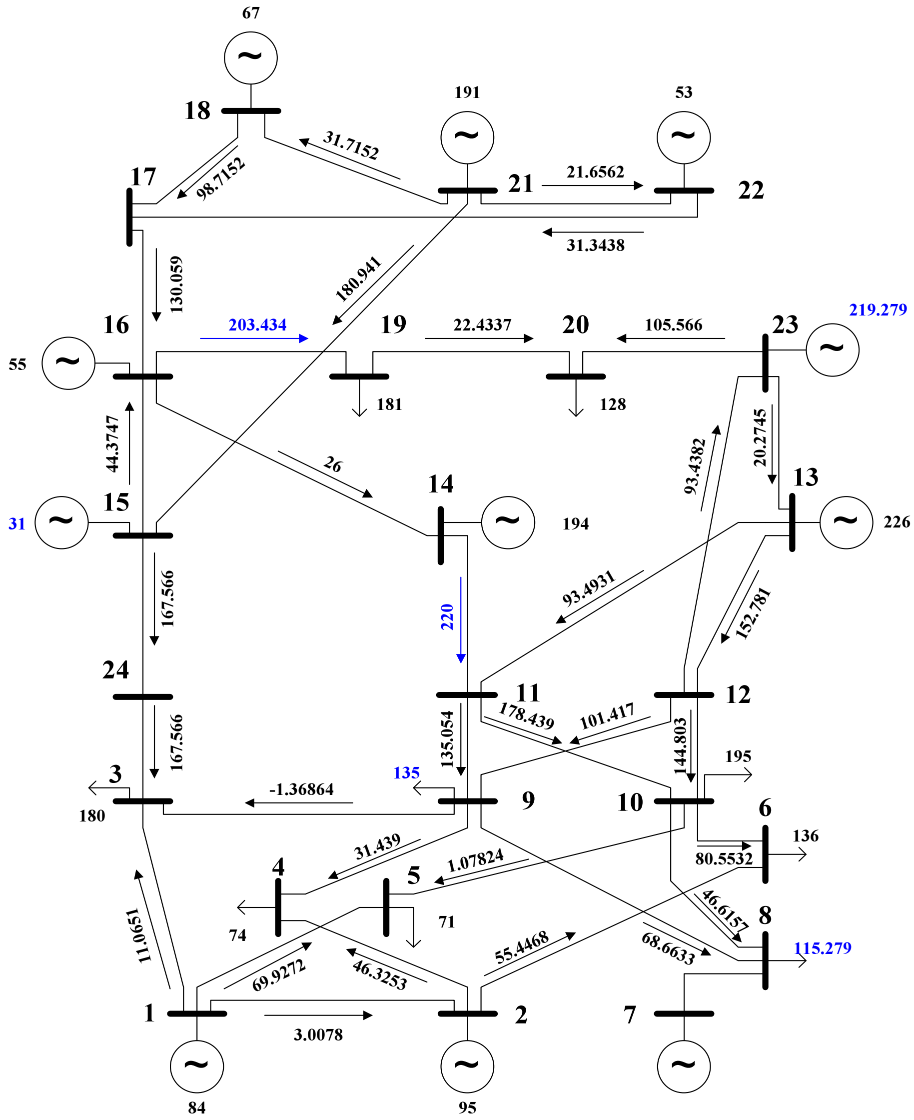

Fig. 2 – IEEE-RTS *network: after relaxation by* LP *procedure.*

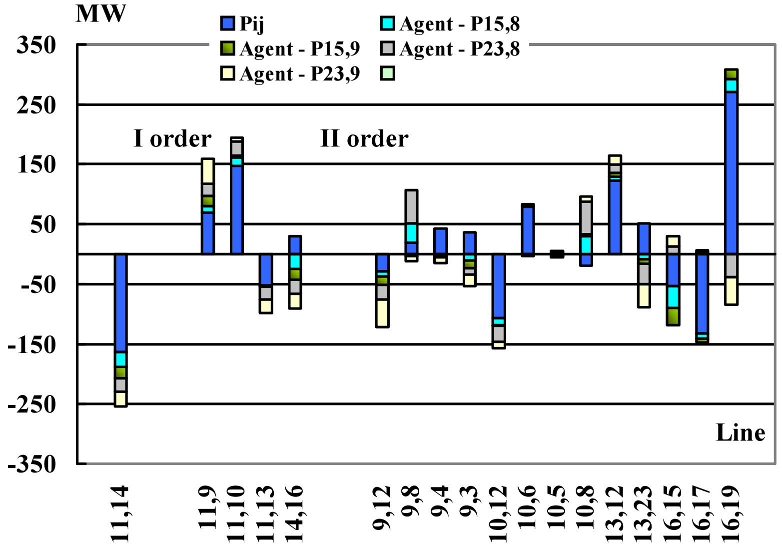

Fig. 3 – I *and* II *order tiers for line* 11-14 *congestion.*

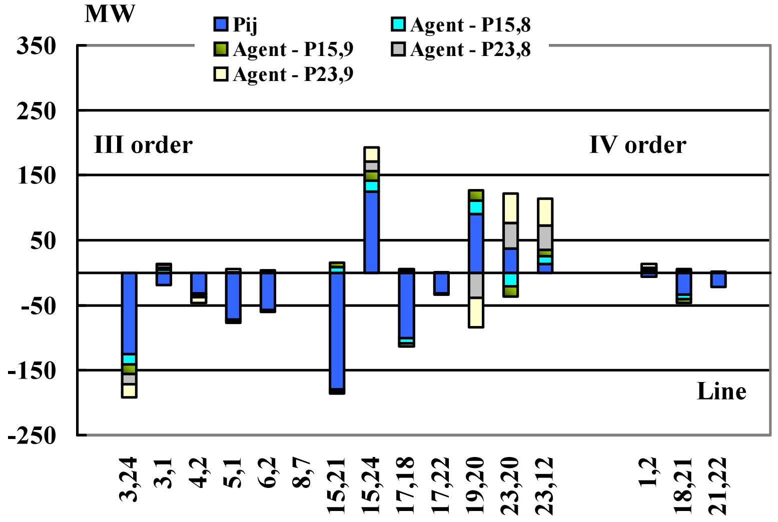

Fig. 4 – III *and* IV *order tiers for line* 11-14 *congestion.*

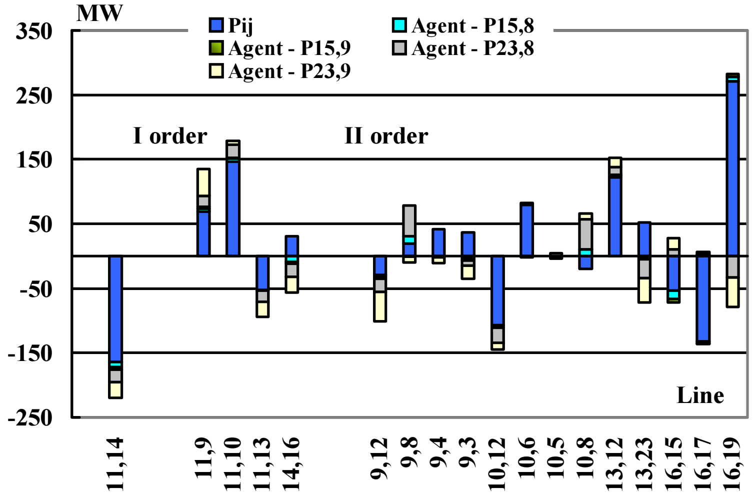

Fig. 5 – I *and* II *order tiers for line* 11-14 *congestion after relaxation by* LP *procedure.*

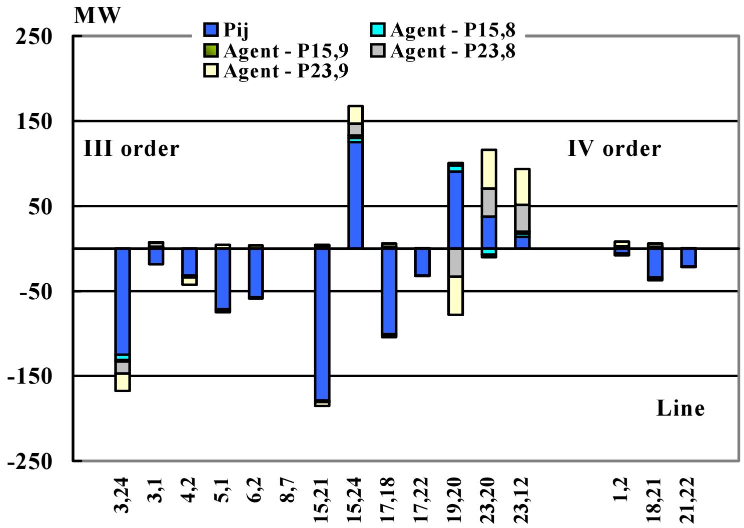

Fig. 6 – III *and* IV *order tiers for line* 11-14 *congestion after relaxation by* LP *procedure.*

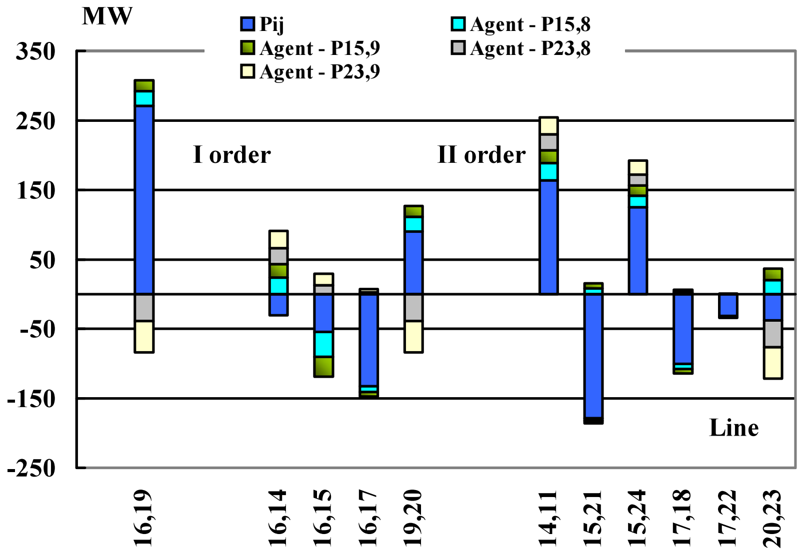

Fig. 7 – I *and* II *order tiers for line* 16-19 *congestion.*

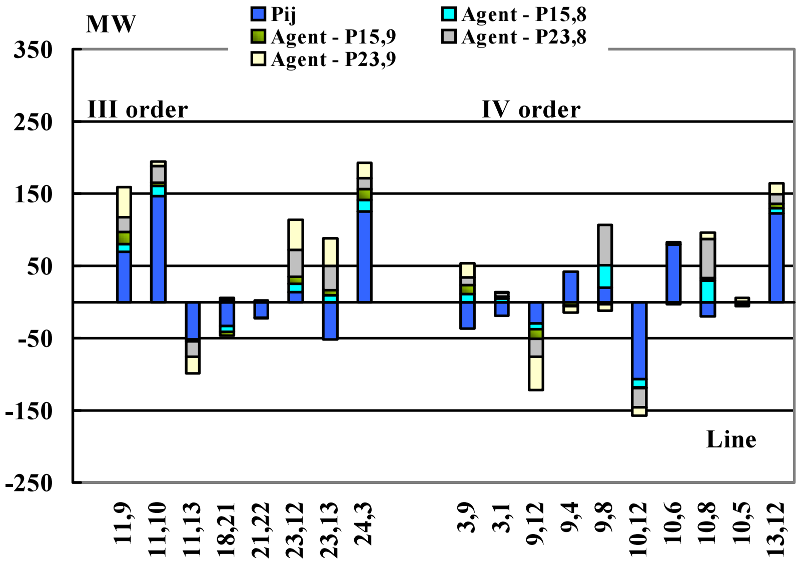

Fig. 8 – III *and* IV *order tiers for line* 16-19 *congestion.*

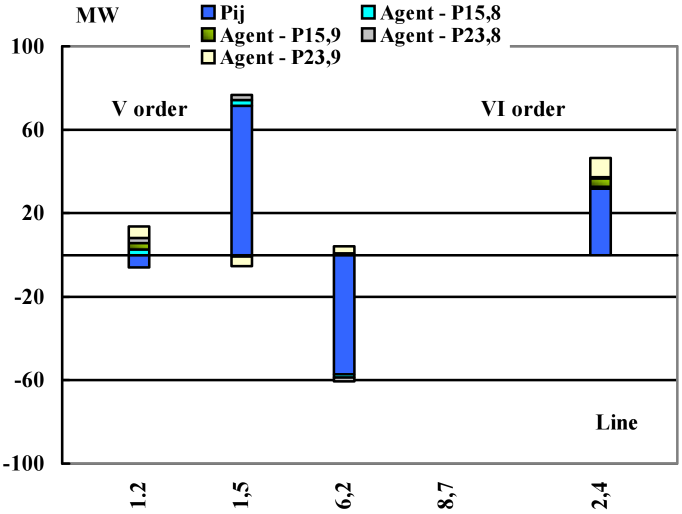

Fig. 9 – V *and* VI *order tiers for line* 16-19 *congestion.*

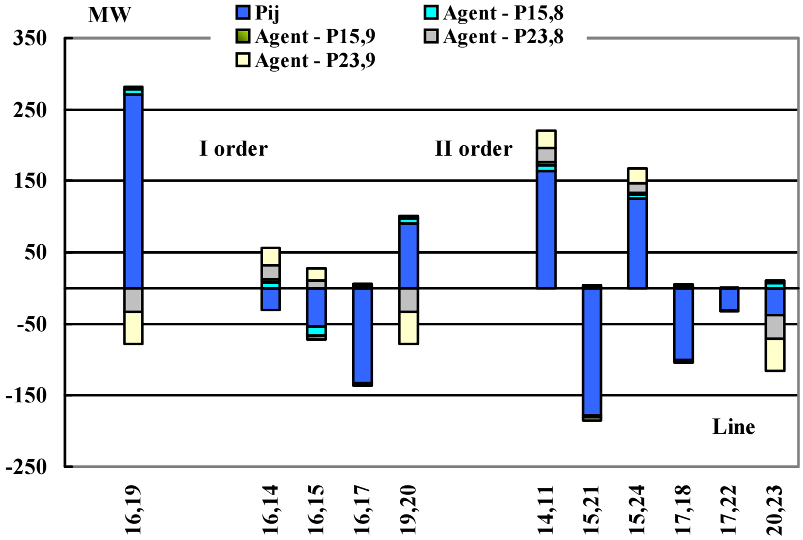

Fig. 10 – I *and* II *order tiers for line* 16-19 *congestion*
after relaxation by LP *procedure.*

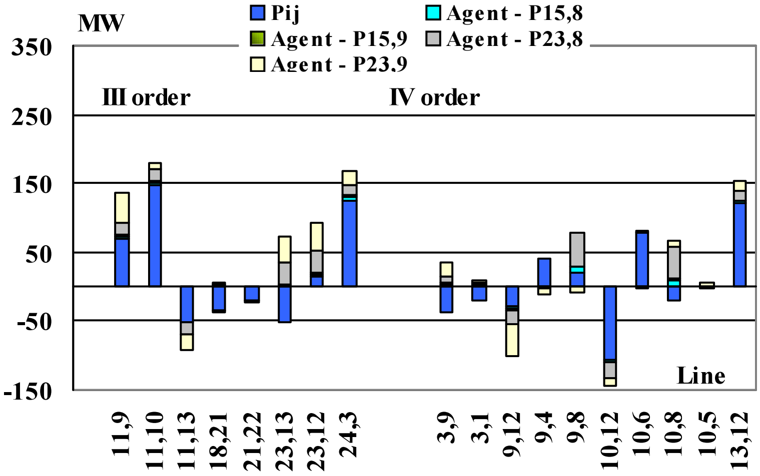

Fig. 11 – III *and* IV *order tiers for line* 11-14 *congestion after relaxation by* LP *procedure*

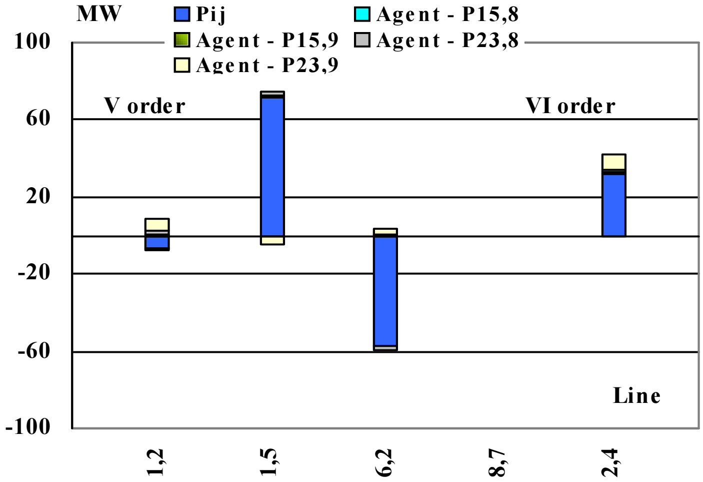

Fig. 12 – V *and* VI *order tiers for line* 16-19 *congestion after relaxation by* LP *procedure*

5 Conclusion

The classical nodal point of view of expressing and visualizing the load flow data is replaced in this paper with the so called “concentric relaxation” method of visualization. This method implies propagation of network searching in tiers, which is a very natural view of displaying the power flow data. The idea is found in the way the drop of water spreads through the cotton cloth fabrics. This is the most proper way to find the effects of the static disturbance, because it is known that the magnitude of the propagation effects is the highest in the vicinity of the disturbance. In that way, the effects of the line congestion and the effects of the congestion management procedure on the same pinpointed line are best observed in the same tier. Tiers could even be used for manual manipulation which could replace the need for optimization procedures. Simulators could naturally do that.

The symbolic analysis method is originally conceptualized and the symbolic simulator is programmed in order to produce analytical, fully/partially derived symbolical expressions [1]. Here, they are used for bilateral transactions (agents). Bilateral transactions come out as expressions – linear combinations of network transfer functions featuring susceptances i.e. Power Transfer Distribution Factors (PTDFs) and power injections.

The form itself of generated transactions as partial/full symbolic transfer functions enables easy handling of agents, visualized as “dominant flows” or “counter flows”. Transaction, which is actually a pair of power injections, could be manipulated as a pair of shoes on a lace, if you pull one, you have pulled also another one, and it is sensed in all network branches.

The exact portion of each flow could be analyzed and appropriate actions taken to reduce the threatening congestion. Besides, the notion of the available transmission capacity (ATC) could also be easily grasped.

The linear programming optimization problem is applied to the generation/load congestion management, with transactions used as system variables.

The code prior to optimization is completely generated by the symbolic analyzer. The symbolically assisted numeric computations are enabled in a systematic way. Multilateral transactions are the linear combinations of bilateral transactions. The effect of variable changes (power injections) could be analyzed, and causes for congestion physically assessed.

The visualization of the spread of so-called natural power flows could be utilized to reduce component flows without sophisticated programs, procedures or power electronic components (e.g. by line or transformer switching or generator rescheduling), but it could also include the models of the latter.

6 List of Symbols and Abbreviations

6.1 Symbols

P_j^0	*j*-th bus generation
$P_j^{\max}, P_j^{\min}$	generator limits
n	number of transactions, $i=1,..,n$
N	number of nodes, $j=1,...,N$
B	number of branches, $l=1,...,b$
DP_i^+, DP_i^-	the *i*-th (of *n*) transaction or agent-flow DP_i upward and downward “shifts”, respectively, positive values
$f_l^{\max}$	the line maximum flow
f_l^0	the base case flow on line
P_j^0	*j*-th bus generation
$P_j^{\max}, P_j^{\min}$	generator upper and lower limits, respectively

6.2 ABBREVIATIONS

DC	Direct Current (load flow method)
AC	Alternating Current (load flow method)
SADCLF	Symbolic Analysis of DC Load Flow (computer program)
BTC	Bilateral Transmission Capacity
ATC	Available Transmission Capacity (Available Transfer Capability)
IEEE RTS	IEEE Reliability Test System
PTDF	Power Transfer Distribution Factor

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