Impacts of Grid Reinforcements on the Strategic Behavior of Power Market Participants

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***Abstract*—Various trends in power systems increase the need for network investments on the transmission level. In this paper we compare different investment criteria and transmission technologies to determine where and how the network should be reinforced. We deploy an agent-based model taking explicitly into account that generation companies might behave strategically by submitting bids to the marketplace deviating from their true marginal cost. In a subsequent step we formulate the optimization problem of the Independent System Operator relying on the well-known Locational Marginal Pricing market design. In a last step the ISO can decide for transmission investments, by reinforcing existing lines or installing Flexible AC Transmission Systems. We show that the decisions regarding which technologies should be used and what locations are to be chosen are not influenced by the strategic behavior of market participants. Additionally, we demonstrate — both analytically and through simulations — that maximizing social welfare as investment criterion complements the objective of mitigating strategic behavior of individual players.**

***Index Terms*—Multi-agent Modeling, Electricity Markets, Strategic Behavior, Network Investments, FACTS**

I. INTRODUCTION

Various trends in power systems increase the need for network investments on the transmission level. On the one hand European energy policy aims at the establishment of a pan-European market as stated in regulation 1228/2003 of the European Parliament [1]. On the other hand, there is a growing need to accommodate the increasing in-feed from renewable energy sources in a secure and economically efficient manner. Other reasons that emphasize the importance of network expansion and reinforcement are e.g. the aging transmission system infrastructure as well as prospective changes on the demand side, such as the shift towards electric mobility. Mostly, investment projects target the removal of congestion in an existing system. However, with a number of diverse drivers for prospective investments (as the ones mentioned above) the question arises if congestion removal is a sufficient decision criterion or if other indicators can be deployed. For instance, the system could be optimized according to economic criteria (welfare, market power, etc.) as well as technical criteria (security of supply, network stability etc.).

One other complication for investment decisions is the fact that transmission capacity expansion might be achieved by means of different technologies. It is possible to reinforce certain interconnections by upgrading the voltage level or by building parallel circuits. Such investments use ‘standard’ overhead high-voltage transmission lines (OHL). Contrastingly, it is possible to target congestion by so-called Flexible AC Transmission Systems (FACTS). Despite the variety of different types of FACTS, in this paper we focus on Thyristor-Controlled-Series-Compensators (TCSCs) as they provide significant flexibility in power flow control. TCSCs allow for altering the line reactance, which in turn leads to a change of network utilization. Certain congested lines may be relieved, where other lines are loaded more ‘heavily’. Hence, a FACTS device does not increase thermal capacity, but it can have a similar effect through changing power flow patterns.[1]

Apart from the different technological alternatives, another difficulty for investment decisions is the fact that national electricity markets often suffer from imperfections originating from historical structures. Although a high number of markets worldwide are nowadays liberalized, the supply side is likely to exhibit characteristics of oligopoly markets. Such a structure typically provides the possibility for strategic behavior.

With regard to this complex framework, the contribution of this paper is an analysis of different decision criteria for investments and their influence on technical and economic system performance. We explicitly compare investment strategies targeting the removal of congestion with the objective of increasing market efficiency by means of limiting the market power of market participants. In terms of investment alternatives, different technologies can be selected, such as the building or reinforcement of ‘conventional’ AC transmission lines or the installation of FACTS devices, in particular Thyristor-Controlled-Series-Compensators (TCSCs). The work can be seen as an extension of [2] and [3] to study investment effects.

The remainder of the paper is organized as follows. Section II presents a synopsis of the entire modeling framework, briefly introducing the different constituents. In Section III we give a brief introduction to reinforcement learning as behavioral agent model together with an outline of the decision problem of generation companies in oligopolistic markets. Section IV details the mathematical formulation of an AC optimal power flow incorporating TCSC devices. A first case study is presented in Section V, where we theoretically justify the results in Section VI. A second case study in Section VII demonstrates the applicability of the proposed approach on a power system capturing the main properties of the transmission system interconnecting Italy, France and Switzerland. Section VIII concludes the paper.

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[1] Also Phase-Shifting Transformers (PSTs) can be used to control the power flow. Although they are based on different operational principles, they act in a similar way as TCSCs during steady-state operation.

II. SYNOPSIS OF THE MODELING FRAMEWORK

The following section is intended to describe the different constituents of the overall model. The aim is to clarify the interactions between the different parts and to provide a motivation for the use of a multi-agent system. Generally, we rely on Locational Marginal Pricing (LMP) as market design.[2] The model is based on the work presented in [3]. However, we briefly outline the main points of the framework for the sake of clarity and readability.

A. Imperfect Markets and Their Modeling Implications

In Section I it has been mentioned that electricity markets typically exhibit oligopoly structures. An oligopoly is characterized by a few large firms on the supply side and by a large number of consumers on the demand side. In such markets the assumptions of perfect competition are violated. This concerns especially the rule that all market participants act as price takers, i.e. that they take the market price as exogenous to their own decisions. With market players being price setters rather than price takers (i.e. having the ability to influence prices), questions of gaming, strategic behavior and market power arise. Research has extensively targeted this particularity as seen for instance in [4], [5], [6], [7], [8], [9], [10], [11]. Different approaches for the analysis of such markets can be used, typically including equilibrium models or multi-agent systems. In the scope of this paper we focus on the latter concept in conjunction with a learning algorithm to account for strategic behavior.

B. A Multi-Agent Model of Electricity Markets

The previous section has indicated that liberalized electricity markets are not perfectly competitive. In contrast to the assumptions of perfect competition, economic entities behave 'bounded rationally' giving way to deviating expectations about market developments, different objectives as well as different strategies. Such a view on markets is represented by so-called multi-agent systems (MAS)[3] When it comes to representing electricity markets as MAS, at least three different types of agents can be identified: generation companies (the supply side), loads (the demand side) and the so-called Independent System Operator (ISO).

Generation Companies Due to the oligopoly structure of electricity markets, generation companies have a potential to exercise strategic behavior / market power. Within the scope of a MAS, we rely on reinforcement learning to model the strategic decision of generation companies (see Subsection III-B).

Loads Above it has been stated that strategic behavior of generators has to be modeled within the scope of our framework. The situation is different for the demand side. An oligopoly is characterized by a few firms on the supply side and by a large number of consumers on the demand side. Hence, the demand side of the market matches one assumption of perfect competition, that is, participants are marginally small compared with the overall market size. Thus, we assume that consumers will take the price as exogenously given.

The Independent System Operator A similar reasoning applies to the Independent System Operator. In markets based on locational marginal pricing, the ISO collects bids and then dispatches generation and loads while obeying the physical constraints of the system. The importance of these functions is recognized in electricity markets worldwide. Extensive regulations exist ensuring that the ISO does not abuse its central role for market operation, leaving only a very limited potential for strategic behavior. Subsequently, we assume the ISO to adhere to its core function, i.e. coordinating trade without distorting it.

C. Representation of the Transmission Network

From a technical viewpoint the network is modeled relying on an AC optimal power flow (AC-OPF), where we use an extended formulation as described in [2] to represent FACTS devices in the power flow problem.

D. Sketch of the Overall Model

Figure 1 provides a graphical representation of the modeling framework. Power suppliers submit bids in the form of linear marginal bid functions to the ISO. Subsequently, the ISO clears the market maximizing social welfare while taking into account the network constraints.

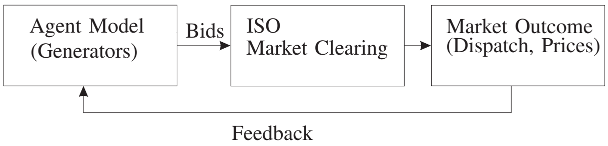

Fig. 1. Flow Chart of Simulator [3]

III. REINFORCEMENT LEARNING AS BEHAVIORAL AGENT MODEL AND DECISION PROBLEM OF GENERATION COMPANIES

A. Reinforcement Learning as Behavioral Agent Model

As outlined above, we rely on a representation of an electricity market as multi-agent system. Such a system has to be simulated over a certain time horizon, giving market participants the possibility to interact. With the process of subsequent interaction it may appear obvious that participants should be able to learn, i.e. to acquire knowledge from past actions and decide for upcoming actions in the context of their previous experience. One concept to model the learning process of agents through repeated interaction is reinforcement learning. (see [17] for a survey). In [18] we have intensively described the modeling of market participants using a reinforcement learning algorithm known as Q-learning. In this paper we refrain from presenting the design principles in full detail. In the context of Q-learning, we assume that the different agents observe the rewards gained from previous actions and use

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[2] Although LMP is to date not implemented in Europe, it allows for an in-depth analysis of the effects of possible network investments. Current European congestion management concepts, such as market coupling (splitting) and explicit auctions represent the network topology in a simplified way, i.e. deploying copperplate representations for each country. Contrastingly, with LMP the representation of the transmission network does not have to be simplified, providing a crucial advantage for a detailed (a line by line) investment analysis.

[3] See [12], [13], [14], [15], [16] for previous applications of MAS to electricity markets.

these observations to adjust their strategy in order to maximize their next reward. When an agent i is modeled by a Q-learning algorithm, it keeps in memory a function $Q_i : A_i \rightarrow R$ such that $Q_i(a_i)$ represents the expected reward it believes it will obtain by playing action a_i out of the space of actions A_i. It then plays with a high probability the action it believes is going to lead to the highest reward (R), observes the reward it obtains and uses this observation to update its estimate of Q_i.

B. Decision Problem of Power Suppliers

As outlined above, suppliers in oligopoly markets may bid strategically above their marginal cost as they realize their possible influence on market prices. Subsequently, we consider that generators may deviate their bids from marginal cost (unknown to the outside world) to increase their profits. In [19] two ways of deviating are discussed: a) changing the slope s_{G_i} of the cost function or b) changing the intercept ic_{G_i}. Figure 2 illustrates these strategic choices for the generators. In this paper we do not take into account slope manipulations. The actions in terms of markup are represented in the Q-learning algorithm described above. Thus, generation companies learn over time which markup maximizes their expected reward.

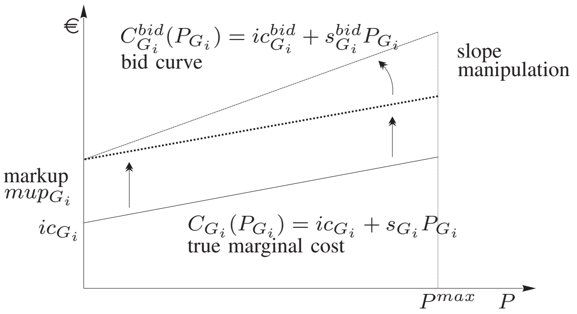

Fig. 2. True Marginal Cost and Strategic Choices

IV. FORMULATION OF THE AC OPTIMAL POWER FLOW INCLUDING TCSCs

A. Standard AC Optimal Power Flow (AC-OPF)

The objective of the standard AC Optimal Power Flow (AC-OPF) is to maximize social welfare (see Eq. 1). The AC-OPF is implemented as follows:

$$max \sum_{j=1}^{N_{load}} C_{L_j}(P_{L_j}) - \sum_{i=1}^{N_{gen}} C^{bid}_{G_i}(P_{G_i}) \tag{1}$$

subject to:

$$f(\theta, V, P, Q) = 0, \tag{2}$$
$$P_{min,k} \leq P_{G,k} \leq P_{max,k}, \tag{3}$$
$$Q_{min,k} \leq Q_{G,k} \leq Q_{max,k}, \tag{4}$$
$$V_{min} \leq V_{bus,k} \leq V_{max}, \tag{5}$$
$$\theta_{ref} = 0, \tag{6}$$
$$|\underline{S}_{kl}(\theta, V)| \leq S_{kl,max}, \tag{7}$$
$$|\underline{S}_{lk}(\theta, V)| \leq S_{lk,max}. \tag{8}$$

Eq. 2 represents the power flow equations as described in [20] and [21]. The remaining constraints refer to the active and reactive power limits of the generators (Eq. 3, 4), the voltage limits of the nodes (Eq. 5) and the line power transfer limits (Eq. 7, 8). Eq. 6 is added, defining the slack bus, where the voltage phase angle is set to zero [22].

B. Additional Constraints for the Inclusion of TCSC devices

In a subsequent step, the AC-OPF is extended with two additional constraints in order to take into account the effects of TCSCs on the OPF solution. Eq. 9 models the TCSC as a variable reactance connected in series with a transmission line. The limits of the TCSC are determined by the constraint (10).

$$r_{kl} + jx_{kl} = r_{line,kl} + j(x_{line,kl} + x_{TCSC,kl}), \tag{9}$$
$$x^{min}_{TCSC,kl} \leq x_{TCSC,kl} \leq x^{max}_{TCSC,kl}, \tag{10}$$

V. CASE STUDY TWO-NODE SYSTEM

A. System Data

Before studying a larger system we provide a case study on a two-node network in order to verify our approach and to gain theoretical insights into the model outcomes. Figure 3 shows the system setup for the first case study.

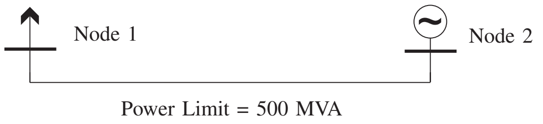

Fig. 3. Topology of the Two Node Network

The network comprises two nodes interconnected by one line. The load is located at node 1, the generator is connected to node 2. The interconnector has a maximum capacity of 500 MVA. We employ linear functions for the marginal willingness to pay of the load and the marginal production cost of the generator. Eq. 11 shows the mathematical representation of the demand curve. Eq. 12 relates to the supply curve.

$$C(P_{L_j}) = n_{L_j} + m_{L_j} \cdot P_{L_j} \tag{11}$$

$$MC(P_{G_i}) = ic_{G_i} + s_{G_i} \cdot P_{G_i} \tag{12}$$

Here, n_{L_j} (ic_{G_i}) denotes the intercept of the demand (supply) functions, where m_{L_j} (s_{G_j}) defines the slope of the demand (supply) function. P_{L_j} (P_{G_j}) indicates the actual power consumed (produced). j (i) is the index for loads (generators). In the two-node example they could be omitted, but they will be used in the subsequent case study, where several generators and loads are present in the system. There are also limits set for the maximum production capacity $P^{max}_{G_i}$ and the maximum limit of demand $P^{max}_{L_j}$ The corresponding data is given in Table I. According to the decision problem of generation companies outlined in Subsection III-B, the generator can behave strategically by setting a markup to its true marginal cost. In that, the generator has three possible bids to submit to the ISO. Either it reveals its marginal cost, or it adds a markup of five or ten percent. These choices are reflected in table I in the column titled markup. On the demand side we do not consider strategic behavior as argued in Subsection II-B. Furthermore, we assume a power factor of 0.95 for each load, leading to a certain demand of reactive power. As this reactive power demand is of minor importance for our analysis, we focus our analysis on active power only. We refrain from presenting the line parameters connecting node 1 and node 2. As there are no parallel paths, and thus, no loop flows, arbitrary values can be chosen without influencing the overall model behavior. Of importance is only the maximum apparent power constraint of 500 MVA.

TABLE I
GENERATION AND LOAD DATA [4]

Node	Generator				Load		
	s_{G_i}	ic_{G_i}	$P_{G_i}^{max}$	mup_{G_i}	m_{L_j}	n_{L_j}	$P_{L_j}^{max}$
1	-	-	-	-	-0.1	70	1400
2	0.013	6.9	1200	{0,5,10}	-	-	-

B. Model Results of the Two-Node Case

As a benchmark, we first clear the market without considering strategic behavior. In that, we run the model reflecting the assumptions of perfect competition. The second column of Table II (Perfect Competition / Base) summarizes the results, where we use a standard set of indicators such as social welfare, producers and consumer surplus, congestion cost (rent) and nodal prices to describe the market performance. Taken as stand-alone values, these results do not offer much potential for interpretation. The only important thing to note is that the line is indeed congested (loaded to its maximum capacity of 500 MVA), inducing congestion cost (a congestion rent for the ISO) of 6458 € and a difference in nodal prices.

TABLE II
WELFARE ANALYSIS FOR PERFECT AND IMPERFECT COMPETITION

	Perfect Competition		**Imperfect Competition**	
	Base	*Upgrade*	*Base*	*Upgrade*
Demand [MWh]	492	590	492	590
Prod. Surplus [€]	168	238	512	649
Cons. Surplus [€]	12086	17415	12086	17415
Congestion Cost [€]	6458	1893	6113	1482
Social Welfare [€]	18712	19546	18367	19135
nodal p. 1 [€/MWh]	20.8	11	20.8	11
nodal p. 2 [€/MWh]	7.6	7.6	8.3	8.3
congestion	yes	yes	yes	yes

We then run the model again with the possibility for strategic behavior. In Section III, presenting the foundations of Q-learning it has been pointed out that agents typically learn during the course of repeated interaction, making it necessary to have a sufficient number of model iterations (1000 in our case) until stable strategies can be deduced. In the two-node system the results seem to be straightforward. As there is only one generator, we face a monopoly situation. Subsequently, it appears somewhat obvious that the generator has market power and chooses its highest possible markup of 10 percent. The actual model outcome confirms our expectations, which is not surprising but shows the accurate functioning of the chosen approach.[5] In comparison with the perfectly competitive markets, social welfare is lower (see Table II Column: Imperfect Competition / Base). The total demand remains at the same level, as the load at node 1 has a limited elasticity. The most interesting result is that the congestion cost decreases by the same amount of money (345 €) that the producer surplus increases. In Section VI a theoretical justification for these results is presented.

To study the influence of network investments we increase the maximum apparent power line limit by 20 percent, i.e we add 100 MVA of capacity. Then we rerun the model, again studying perfect and imperfect competition. In the latter case the optimal strategy for the generator is still to add a markup of 10 percent to its true marginal cost. In both cases (perfect and imperfect), social welfare is increasing, showing the beneficial effect of network investments on the market. Congestion cost and the difference in nodal prices both decrease as we relaxed the line limit. However, congestion is still persistent. Note that the producer surplus in both cases increases. This effect is due to a lower nodal price at node 1, and thus, higher demand. The additional demand is satisfied by the generator. However, the generator 'consumes' again a part of the congestion rent in the imperfect case. Comparing the perfectly competitive case with the imperfect case (considering the line upgrade), the difference in congestion cost amounts to 411 €. This amount of money exactly represents the increase of producer surplus. Based on these results it is possible to define a market power index derived from the relative gain in producer surplus compared with the perfectly competitive case. In other words, the market power index shows the potential increase of producer surplus by behaving strategically. Before the investment the index amounts to 512 € / 168 € = 3.05. This means that generators are able to triple their surplus. After the investment the index is given by 649 € / 238 € = 2.73. The decrease demonstrates that the transmission investment limits the effects of market power. We will discuss these results in the light of microeconomic theory in the following section.

VI. DISCUSSION OF CASE STUDY RESULTS APPLYING MICROECONOMIC THEORY

The following section is intended to justify the findings of the case study using microeconomic theory. Special emphasis is put on the question why the maximization of social welfare as investment criterion implicitly leads to an optimal solution also in terms of mitigating market power.

A. Social Welfare in Perfectly Competitive Markets

Figure 4 provides a graphical definition of welfare in perfectly competitive markets. Demand and supply of the market are represented by linear functions, where the intersection

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[4] s_{G_i} and m_{L_j} are given in €/MWh; ic_{G_i} and n_{L_j} in €; $P_{G_i}^{max}$ in MW. We assume no costs and no limits for the production of reactive power. The load in the system is assigned a power factor of 0.95 leading to a certain reactive power demand.

[5] The deduction of the optimal strategies of generators relies on the Q-functions. In the scope of this paper we refrain from presenting the underlying theory. A comprehensive treatment can be for instance found in [3].

of the curves determines the equilibrium point, characterized by the market clearing quantity (q_m) as well as the market clearing price (p_m). The triangular space enclosed by the aggregated marginal cost curve (supply curve) and the market clearing price (p_m) is known as producers' surplus (PS). The consumers' surplus (CS) is represented by the area enclosed by the demand curve and the market clearing price (p_m). Consumers' and producers' surplus amount to the total surplus, i.e. they amount to overall social welfare. In perfectly competitive markets welfare is at its maximum (see the results of the previous case study).

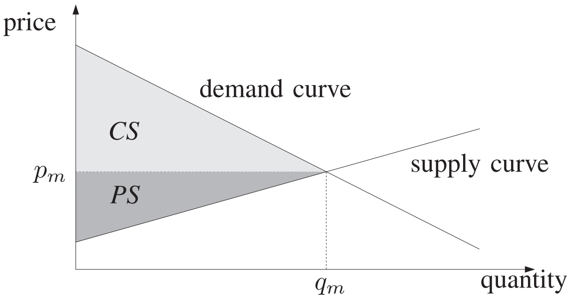

Fig. 4. Concept of social welfare, with p_m denoting the market clearing price and q_m the market clearing quantity as well as CS being the consumers' surplus and PS the producers' surplus.

B. Social Welfare in the Presence of Congestion

The representation in Figure 4 does not hold true in the presence of network constraints. Figure 5 shows the new setup.

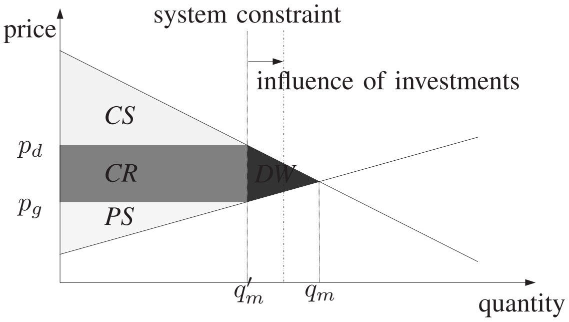

Fig. 5. Social Welfare and transmission congestion with CR being the congestion rent, DW the deadweight loss, q_m the unconstrained clearing quantity, q'_m the clearing quantity in case of congestion and p_d and q_d the resulting clearing prices. Labels for demand and supply curve omitted for readability reasons.

Due to network congestion the original equilibrium point (q_m) cannot be reached. Although there is still one market clearing quantity (q'_m), in the quasi-equilibrium point two prices exist: one related to the consumers' willingness to pay (p_d) and one given by the marginal cost of production (p_g). Discussing this situation from the viewpoint of the ISO, the ISO would buy electricity at the price of (p_g) and sell it to the consumer at the price of (p_d), as this reflects the willingness to pay at the demand side. Hence, the ISO collects a rent, which is known as the so-called congestion rent (CR). The triangular left to the congestion rent represents the deadweight loss (DW). The deadweight loss is incurred by the fact that less energy can be traded leading to a loss of welfare in general.

C. The Effect of Network Investments on Social Welfare

The effect of investments in perfectly competitive markets is straightforward. As congestion is relieved through network expansion / reinforcement, the market clearing quantity (q'_m) increases. Graphically speaking, the line representing the system constraint moves closer to the original equilibrium point (q_m). In this way the deadweight loss is decreasing leading to a welfare increase.

D. Social Welfare in the Presence of Congestion and Market Power

If we remove the assumption of generation companies behaving perfectly competitive by revealing their true marginal cost, we again face the decision problem outlined in Subsection III-B. Generation companies may add a markup to their marginal cost curve.

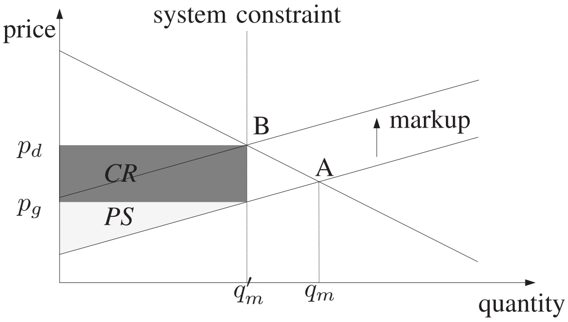

Fig. 6. Effect of market power on social welfare and congestion rent. CS and DW omitted for readability reasons.

Considering Figure 6 such a markup represents an upward shift of the supply curve until an intersection with point B is reached. In doing so, generators eliminate their part of the deadweight loss while they also increase their surplus. Due to congestion, higher bids do not incur any demand effects, as the part of the demand curve enclosed by points A and B is anyway constrained off. The profit of generators is now given by the product ($p_d \cdot q'_m$), not as before by ($p_g \cdot q'_m$). Generators exercise their market power 'consuming up' the congestion rent (CR). This effect can be explained with the shift of the supply curve up to an intersection with point B (lying on the system limit). Following this view, we also see a clear dependence of market power and congestion. Obviously, a constrained system 'offers' the possibility for strategic behavior, where the extent of the potential market power exercise is given by the severity of congestion. In turn, the congestion rent can be taken as a measure for severity. Or, in other words, generators try to adapt their strategies until they 'skim' the marginal willingness to pay of the loads at the system limit. It might be argued how such a shift of the supply curve will happen in a 'real' market. A possible explanation is an understanding of markets, where participants learn through repeated interaction (the approach we followed by employing a Q-learning algorithm).

E. The Effect of Network Investments on Market Power

In Subsection VI-C we have shown that a network investment leads to a shift of the system constraint to the right, partially recovering the deadweight loss. In this way also a part of the demand curve is ‘freed’ (enclosed between points B and C), i.e. it re-enters the market. If the supply curve remained as depicted in Figure 7 intersecting with point B (the former system limit), generators would lose profit by not covering the additional part of demand introduced by the network investment (line segment B to C). It seems rational that the supply curve will (through repeated interaction) shift until it intersects in point C with the new system limit (after the investment). This way generators ‘capture’ the additional demand while still exploiting their remaining market power. From this observation it becomes clear why congestion removal is synonymous to mitigating strategic behavior. The latter is only possible because of system constraints. If we remove congestion, the market benefits from a recovery of the deadweight loss as well as the mitigation of market power. Obviously, these two objectives are complementary.

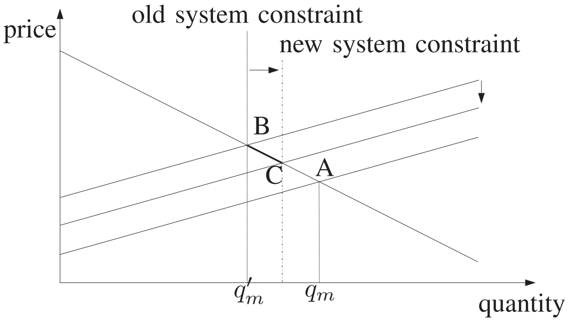

Fig. 7. Effect of investment on market power. CS, CR, DW and PS omitted for readability reasons.

VII. CASE STUDY ITALY-FRANCE-SWITZERLAND MODEL

A. System Data and Modeling Assumptions

Figure 8 depicts the network used for the subsequent case study. It captures the main properties of the system interconnecting Italy, Switzerland and France. Cheap generation units are mostly located in France (nuclear power station) and in Switzerland (hydro and nuclear power), where in Italy generation costs are higher in comparison with the neighboring countries. Due to this geographical dispersion of generation, line number 5 (between node 2 and node 10) interconnecting Switzerland and Italy is usually congested. In accordance with the previous two-node case, linear representations for the demand and supply curves are chosen. The coefficients are summarized in the appendix in Table IV. Table V collects the line parameters.

B. Perfect Competition

We first run the model without considering strategic behavior. The first column of Table III displays the results. Line 5 (interconnecting node 2 and 10) is indeed congested, leading to a difference in nodal prices in the system as well as a congestion rent. The results from this perfectly competitive case will serve as basis for further evaluation.

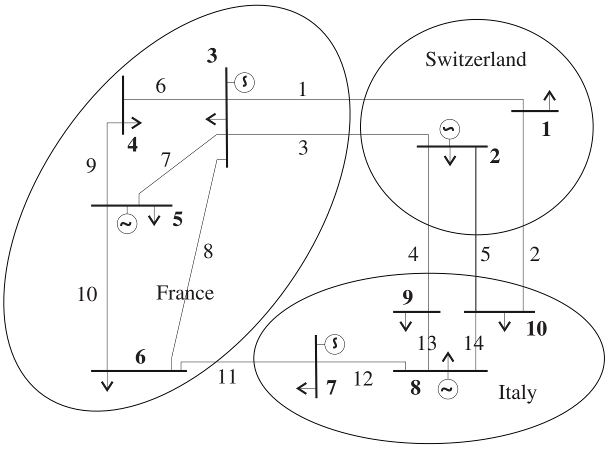

Fig. 8. Interconnected network of France, Italy and Switzerland

C. Perfect Competition with Investment Decision

We choose social welfare as investment criterion, i.e. we decide for the investment option that gives the highest increase in social welfare. In doing so, we are taking a societal view or regulator’s view on investments. For that we first run the model fourteen times (once for each line in the system) to find the best location for a line upgrade. Results suggest that line 5 should be reinforced, which might appear obvious as it is the congested line. The placement of a TCSC is not straightforward as TCSCs can influence the power flow pattern in the network. Running the model, we find that the welfare increase is at maximum if a TCSC is installed in line 11. The result can be explained by looking on the network topology. Line 11 is a parallel path to the congested line 5. With a TCSC influencing the reactance of line 11, more power is flowing through France into Italy relieving congestion between Switzerland and Italy. The findings seem interesting in the sense that for relieving problems in certain corridors, investments at other locations might be required (even in other countries). Table III provides an overview of the results. It becomes also obvious that in our example a line should be preferred over a TCSC as it offers the highest increase in welfare. It should be noted that the upgrade of line 5 leads to congestion between France and Switzerland. However, this congestion is not as severe (Lagrangian multiplier of 10 €/MVA). (See the following section for a discussion of Langragian multipliers.)

D. Imperfect Competition

We now remove the assumption of perfect competition and allow for strategic behavior. From the multi-agent model in conjunction with an evaluation of the Q-functions we find that the Generator at nodes 3 and 8 have market power, i.e. they choose a markup of 10 percent to add on their true marginal cost. Furthermore, results show that social welfare in total is lower, consumer surplus has decreased while producer surplus has increased. The most interesting finding is that the congestion rent is also higher in comparison with the perfectly competitive case. At first sight, the results seem to contradict the findings of the two-node case as the congestion rent is

TABLE III
WELFARE ANALYSIS FOR INVESTMENTS UNDER PERFECT AND IMPERFECT COMPETITION

	Perfect Competition			**Imperfect Competition**		
	Base	*Line*	*TCSC*	*Base*	*Line*	*TCSC*
Optimal Invest. Location (Line No.)	-	5	11	-	5	11
Total Demand [MWh]	11630	11686	11672	11403	11601	11447
Producer Surplus [€ for base cases]	68039	+36.1%	+4.3%	98856	+17.6%	+1.8%
Consumer Surplus [€ for base cases]	1265418	+3.3%	+1.1%	1223295	+6.3%	+1.1%
Congestion Cost [€ for base cases]	114028	-38.8%	-4.1%	124899	-57.0%	-3.2%
Social Welfare [€ for base cases]	1447485	+1.6%	+0.8%	1427613	+1.7%	+0.9%
Minimum Nodal Price [€/MWh] (Node)	23.0 (2)	30.3 (3)	23.5 (2)	24.7 (2)	32.6 (3)	25.1 (2)
Maximum Nodal Price [€/MWh] (Node)	55.7 (10)	46.1 (8)	54.3 (10)	60.5 (10)	46.0 (8)	59.0 (10)
Number of Congested Line (Node - Node)	5 (2-10)	3 (2-3)	5 (2-10)	5 (2-10)	3 (2-3)	5 (2-10)
Shadow Price of Congested Line [€/MVA]	-50.1	-10	-47.5	-54.8	-5.5	-52.7

obviously increasing despite of the strategic behavior of the generators. An explanation for this phenomenon can be found by analyzing the Lagrangian multipliers of the transmission lines derived from the optimization problem. The absolute value of these multipliers indicate the increase in welfare resulting from a relaxation of the line limit of the congested line by a small increment (in practice often 1 MW). In that, these multipliers are often referred to as shadow prices, as they implicitly measure the scarcity of the transmission resources. Comparing the Lagrangian multipliers for the cases of perfect and imperfect competition, we find a higher value for the imperfect case (see Table III). This observation suggests that generators in some cases may deliberately 'tune' their bidding strategies in order to 'worsen' congestion in the network. Figure 9 provides a graphical interpretation of the finding.

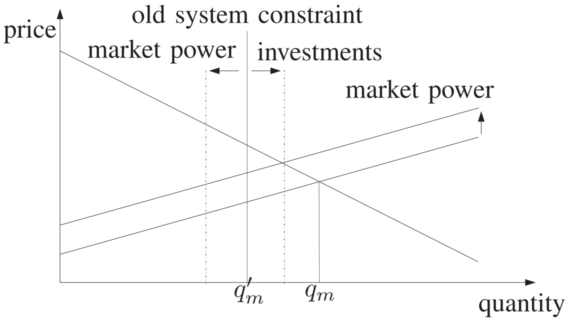

Fig. 9. Effect of strategic behavior on system limits. CS, CR, DW and PS omitted for readability reasons.

In contrast with the previous two-node case where we treated the system limit as exogenous, we now face a situation where the system limit is influenced by strategic bidding. Graphically speaking, the limit is shifted to the left. As demand is rather inelastic, this shift causes a strong increase in the congestion cost. As shown in the two-node example, generators 'consume' the congestion rent by their strategic behavior. In the ten-node example the same effect takes place, but the effect is overcompensated by the total rise in congestion rent. Any network investment will counter the causes of strategic behavior, eventually justifying our initial findings.

E. Imperfect Competition with Investment Decision

Considering investments under imperfect conditions, we find the same optimal locations as in the previous case: an upgrade of line 5 and an installation of a TCSC in line 11. Obviously, strategic behavior does not change the investment strategy derived under perfect competition. It is interesting to note that for the line upgrade the congestion rent decreases in comparison with the perfectly competitive case. We investigated this behavior. For the line upgrade congestion 'moves' from the border between Italy and Switzerland to the border between France and Switzerland. As pointed out above this 'new' congestion on line 3 is not as severe as on line 5, i.e. the difference in nodal prices on either ends of the line is lower. Thus, generators at node 3 and 5 are better off not behaving strategically as the additional surplus from 'worsening' congestion is lower than the additional surplus gained from selling more power at a slightly lower price.

VIII. CONCLUSION

In this paper we chose an agent-based approach to build a market based on Locational Marginal Pricing. By modeling market participants as adaptive agents in oligopolistic structures, we considered the possibility of strategic behavior and the existence/exercise of market power. The market clearing problem of the Independent System Operator (ISO) was formulated to allow studying network investments by 'conventionally' reinforcing lines or by installing FACTS devices, in particular Thyristor-Controlled-Series-Compensators (TCSCs). Our objective was to compare different investment criteria and transmission technologies to determine where and how the network should be reinforced. We came to the following conclusions:

- Transmission investments - independent of the specific technology - counter the effect introduced by the exercise of market power. In particular we have shown that it is not necessary to develop "isolated" investment strategies. Congestion removal and mitigation of market power are synonymous being influenced in an almost identical way from investment measures. This result may prove relevant for policy makers and investors as it reduces the complexity of prospective decisions making it possible to narrow the investment focus.
- Although in a small system (see two-node case) the strategic behavior can be easily motivated and explained,

in a larger, meshed system the exercise of market power is dependent on a number of different factors, and thus, not straightforward to analyze. From a modeling viewpoint it seems necessary to rely on multi-agent systems in order to represent the complex interactions between market participants and the technical system. Nevertheless, even in larger systems it can be shown that investments which improve social welfare will mitigate market power.

- Concerning the use of TCSCs it is possible that the optimal investment location does not coincide with the congested line. This emphasizes the fact that transmission investment is a European issue rather than a national one.

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APPENDIX

TABLE IV
GENERATION AND LOAD DATA (FRANCE, ITALY, SWITZERLAND)

Bus	Generator				Load		
	s_{G_i}	ic_{G_i}	$P^{max}_{G_i}$	mup_{G_i}	m_{L_j}	n_{L_j}	$P^{max}_{L_j}$
1	-	-	-	-	-0.1	35.5	65
2	0.00134	6.9	1200	{0,5,10}	-0.1	35.5	65
3	0.0008	24.3	8000	{0,5,10}	-0.1	160	1400
4	-	-	-	-	-0.1	95	750
5	0.00012	29.1	3000	{0,5,10}	-0.1	95	750
6	-	-	-	-	-0.1	230	300
7	0.00052	6.9	800	{0,5,10}	-0.1	290	2700
8	0.003	50	2000	{0,5,10}	-0.1	390	3700
9	-	-	-	-	-0.1	140	1200
10	-	-	-	-	-0.1	230	2000

Here, s_{G_i} and m_{L_j} are given in €/MWh; ic_{G_i} and n_{L_j} in €; $P^{max}_{G_i}$ and $P^{max}_{L_j}$ in MW. We assume no costs and no limits for the production of reactive power. Each load in the system is assigned a power factor of 0.95 leading also to a reactive power demand.

TABLE V
TRANSMISSION LINE PARAMETERS ($S_{base} = 1000$ MVA)

from # bus	to # bus	R [p.u.]	X [p.u.]	B [p.u.]	S^{max}_{kl} [MVA]
1	3	0.04	0.10	0.04	3000
1	10	0.08	0.27	0.08	2000
2	3	0.01	0.12	0.01	3500
2	9	0.02	0.07	0.02	2260
2	10	0.02	0.14	0.02	1580
3	4	0.02	0.10	0.02	1780
3	5	0.02	0.17	0.02	2150
3	6	0.02	0.17	0.02	3500
4	5	0.02	0.17	0.02	2150
5	6	0.02	0.17	0.02	2800
6	7	0.01	0.16	0.01	3500
7	8	0.01	0.25	0.01	2000
8	9	0.01	0.25	0.01	2260
8	10	0.04	0.07	0.04	3500