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# Reactive Power Provision to TSO/DSO by Aggregators and Conventional Generators

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***Abstract*—Reactive power management is one of the imperative ancillary services provided by TSO (Transmission System Operator). This reactive power imbalance mainly occurs at transmission levels, and TSO pays generators for managing reactive power. DSO (Distribution System Operator), DER (Distributed Energy Resources), and DG (Distributed Generators) cannot take part in this provision to TSO due to regulations, specifically in Italy. The paper discusses the needs for reactive power management, and comparison of different existing compensation techniques. It talks about the regulatory restrictions, and some proposals for changes, for participation in ancillary market. The paper then discusses about the use of DER as an aggregated virtual power plant to serve as reactive power compensation technique.**

## I. INTRODUCTION

Reactive power exists in AC circuits when voltage and current are not in phase due to inductive or capacitive effects. These effects can be on generation, transmission, and distribution sides of power system.For inductor, voltage leads current, and the reverse is true for capacitor [1]. Thus, the direction of power is reverse for both, and as a convention, it is considered that capacitors produce reactive power, while inductors consume it. For voltage stability, reactive power generation should be equal to reactive power consumption.

Reactive power imbalance can have adverse effects on power systems. For example, decrease of reactive power for a load causes voltage drop. For real power P, the voltage drop causes current to increase through the load, and this can damage the load. If this voltage drop increases further, generators are tripped to ensure safety, and thus the situation becomes worse (with further voltage drop) [2].

Transmission line is the main cause of reactive power mismatch. It has both inductive and capacitive effects, and therefore it can create both increase and decrease in reactive power while the real power is carried along transmission line [3]. Increase in reactive power will cause voltage rise, while decrease will cause voltage drop along the transmission line.

At the distribution level, this reactive power imbalance will take place because of the inductive nature of the majority of the loads. Variation in demand at load side is another parameter for the reactive power effect. Increase in demand causes increase in inductive reactive power at distribution end (or additional reactive power is consumed at the transmission level). Decrease in demand causes increase in capacitive reactive power at distribution end (or additional reactive power is generated at the transmission level).Thus, the voltage stability is at stake at the distribution end too.

Failure of generators and transmission lines can increase the demand further, and the above-mentioned effects can take place again. TSO and DSO play their roles to control this reactive power mismatch. Particularly in Italy, TSO remunerates generators for reactive power. Other than that, there may be some penalty charges for DSO or customers for creating additional reactive power mismatch.

The paper is arranged in this way: Second section talks about different techniques for the compensation of reactive power. Section three discusses the regulatory restrictions for the participation to ancillary services by the distributed resources, and some of the literature suggestions. Section four discusses how these aggregated resources can be used together with the conventional techniques. Section five concludes the paper. Appendix discusses the theoretical validation of the proposed work, as discussed in the above-mentioned sections, and the future work.

## II. TECHNIQUES FOR REACTIVE POWER COMPENSATION

At the distribution level, the minor variations in voltage are dealt with VOLT/VAR control (also called as Distribution System Voltage Control). These minor changes during the daily operations may cause both under and over voltage violations. The technologies are OLTC (On Load Tap Changers) and capacitor banks. The controller manages the taps of both, and checks for voltage limits at nodes. The reactive power provided here is not at the expense of real power, and the only capital cost is the installation of controllers, capacitors, and OLTC.

At the generation level, the primary voltage control is provided by AVR (Automatic Voltage Regulator). It is a

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controller that regulates the terminal voltage of synchronous generator. However, PSS (Power System Stabilizer) is also used for further improving stability. These controls are sufficient for reactive power (voltage control) at the generating end of power system.

Therefore, the main problem causer is the transmission level, which requires reactive power compensation techniques. The conventional method is to use synchronous generators (at generation side) for reactive power compensation resulting from reactive power imbalance at transmission level. Conventional power plants have synchronous generators to supply/absorb reactive power. The power capability curve of synchronous generator illustrates that a generator can produce (over-excitation), as well as consume (under-excitation) reactive power at the expense of real power.

However, there are some limitations for these synchronous generators in order to provide the provision of reactive power. As synchronous generators are designed to produce real power, and not reactive power, therefore the main issue is the loss of real power here due to reactive power. They utilize a significant portion of real power capability. It is thus clear that it is not very efficient to utilize them for the purpose of reactive power. The real power is limited by the size of turbine, and the reactive power has the limitation of the size of synchronous generator. Therefore, increase in reactive power means more investment in terms of increase in ratings of turbine and synchronous generator. There are also other limitations of rotor winding, stator winding, over-excitation, under-excitation etc.

There are other techniques to relax the reactive power requirements for conventional synchronous generators, and different levels of power system have these techniques in place. One of the static techniques is the use of a combination of switched capacitors. They are a source of reactive power to the system. This method is the cheapest amongst reactive power compensation methods, and there is no loss of real power due to reactive power.

However, the reactive power varies with voltage in a square relation (the capacitor equation), and thus the method is only suited for low and medium voltages. For high voltage applications, and the applications where the voltage is a critical phenomenon (like the trip of voltage relays in power system protection domain), the switched capacitor is not a proper option.

Another technique is the use of synchronous condensers. They are synchronous generators which serve the purpose of compensation of reactive power only, and not the real power. They consume a little portion of real power to provide reactive power capacity. However, for this dynamic technique, the maintenance and conversion costs are high.

SVC (Synchronous Voltage Condensers) is another technique, employing switched capacitors as a part. Consequently, it still has the same issue of non-linear voltage dependency. Another one is the STATCOM (Static Synchronous Compensator), a dynamic technique, with power electronics current controlled devices, in place of voltage-controlled capacitors, and thus the above-mentioned problem is eliminated. The cost here is higher than switched capacitors, but lower than that of synchronous condensers. There is also no loss of real power due to reactive power.

Wind farms are very common in this modern era. They use asynchronous induction machines to convert wind to electricity. Thus, in order to synchronize with the grid, these wind farm generators use power converters (AC-DC-AC). This AC-DC-AC power conversion can provide independent control of reactive power. Again, the reactive power is not dependent on real power for this dynamic technique. However, in order to maintain a continuous power factor and independent control of reactive power, it is required to oversize the converter by 10% of the generator's rating [4].

Solar panels are also very common these days. They use MPPT (Maximum Power Point Tracking), and Inverters to convert solar energy into electricity. These inverters can also be used to provide reactive power control. For this dynamic technique, the reactive power is dependent on real power. For oversizing of inverters by 10% of generator's capacity, the system can provide 46% reactive power at 100% real power OR 110% reactive power at zero real power [4].

Wind farm converters have the limitations of terminal voltage, and inverters have limitations of terminal voltage, real power produced by PV panels, and current rating for the production of reactive power. Another point of interest is the production of reactive power at zero (or very low) wind and solar energy. Companies have already implemented such converters, and literature suggests the same with capability curves for these technologies. However, it requires keeping the plants grid-connected even at no wind and sun.

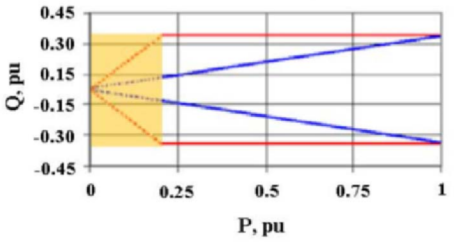

Fig. 1: Reactive power VS. Real power capability for wind farm converters; taken from [5]

As seen from Fig. 1 [5], there is capability of producing reactive power at zero real power. P and Q are the real power and reactive power respectively in per-unit(pu) at the point of interconnection (with 0.95 power factor, at rated output) with different combinations. However, this reactive power provision is not enough as compared to the imbalances, and therefore cannot fully replace the conventional synchronous generators.

## III. Italian Regulations for Ancillary Services, and Proposals for Amendments

According to current Italian regulations, any production unit based on intermittent resources cannot participate to services market. In addition, the production units cannot be from the distribution side of power system. These facts restrict the distributed resources and aggregators to participate to the services market [6] [7].

Other European countries like Belgium, France, and UK allow these aggregators for participation into the services market, and therefore Italian regulations will allow these aggregators to participate as well from 2018 [8] [9]. Italy is divided into six geographical zones; the regulations will restrict inter-zonal aggregation, and mixed aggregation (loads and generators together) [6] [7]. The restriction of regulations create hurdle as TSO can only get services from generators, and customers only have the option of interaction with their specific DSO. The idea is to allow TSO to get services from these aggregators, and enable customers to offer their services to any market (energy or service) [10].

Keeping in mind the optimistic change in regulations in future, literature suggests that there should be a single marketplace for balancing and flexibility. TSO-DSO can interact with each other, and increase the observability of each other for efficient utilization of resources, and resolution of congestion management for each other. The proposal leads towards mutual reactive power management, where TSO can ask reactive power control from DSO [10] [11]. A possible scheme is also discussed, as shown in Fig. 2 [12], where aggregators can communicate directly with the DER, and aggregators can participate too directly to ancillary market. As a matter of terminologies, DNO (Distribution Network Operator) and ISO (Independent System Operator) are used interchangeably for DSO and TSO respectively.

## IV. Proposed Approach

Nowadays, DER are very prevalent, and causes significant impacts on power systems. One of the relevant adverse effects is the reactive power mismatch at distribution level, which makes the grid active. Therefore, VOLT/VAR control is the commonly used technique to counter such issue.

In the context of TSO dispatch of reactive power from generators, the scenario gives rise to three options. One is the conventional way of synchronous generators, together with STATCOMs, for reactive power provision. This combines the benefits of low operating costs (compared with synchronous generators), and no loss of real power for reactive power provision, for conventional generators.

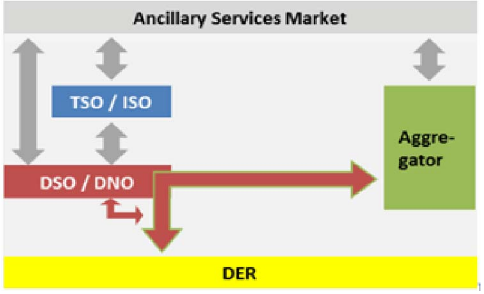

Fig. 2: Aggregators direct access to DERs and Ancillary Market; taken from [12]

Another way is the use of DFIG (Doubly-Fed Induction Generators) based wind plants converters, and solar inverters for reactive power provision, together with synchronous generators. However, as these plants are not designed solely for the purpose of reactive power provision,their capital and operating costs are much lower than the conventional synchronous generators. This combines the benefits of low costs and capability to provide reactive power at zero or very low active power, for conventional generators.

The new way is the use of aggregators to participate in the ancillary market provision for TSO, together with the conventional synchronous generators. These aggregators utilize DER, and DR (Demand Response) at customer end, together with DG, and storage at commercial levels. Infact, the aggregator can feed from or feed to generators as auxiliary load (double peaker power plants), and/or storage. This gives benefits to VOLT/VAR control, and relaxation to conventional generators by utilizing the resources at distribution end (and other third party, or generators) by interacting directly with TSO.

The proposed approach is shown in the architecture in Fig. 3.TSO has the opportunity to get reactive power from conventional synchronous generators, with the utilization of STATCOM, DFIG based converters, PV inverters, and aggregators. The controller at TSO can decide the provision of services based on cost, availability, and offered flexibility.

Another way of interpretation of this approach is the improvement in the conventional technique of reactive power provision through conventional coal and combined cycle generating units. STATCOMs can be installed at the generating units to compensate for the shortcomings by synchronous generators. Existing DFIG based wind and solar plants can be used to provide a component of reactive power provision. In addition, storage and auxiliary loads at conventional plants can be considered as sources of reactive power provision. The details of flexibility generated by auxiliary loads at conventional power plants is discussed in the sub-section following the proposed approach.

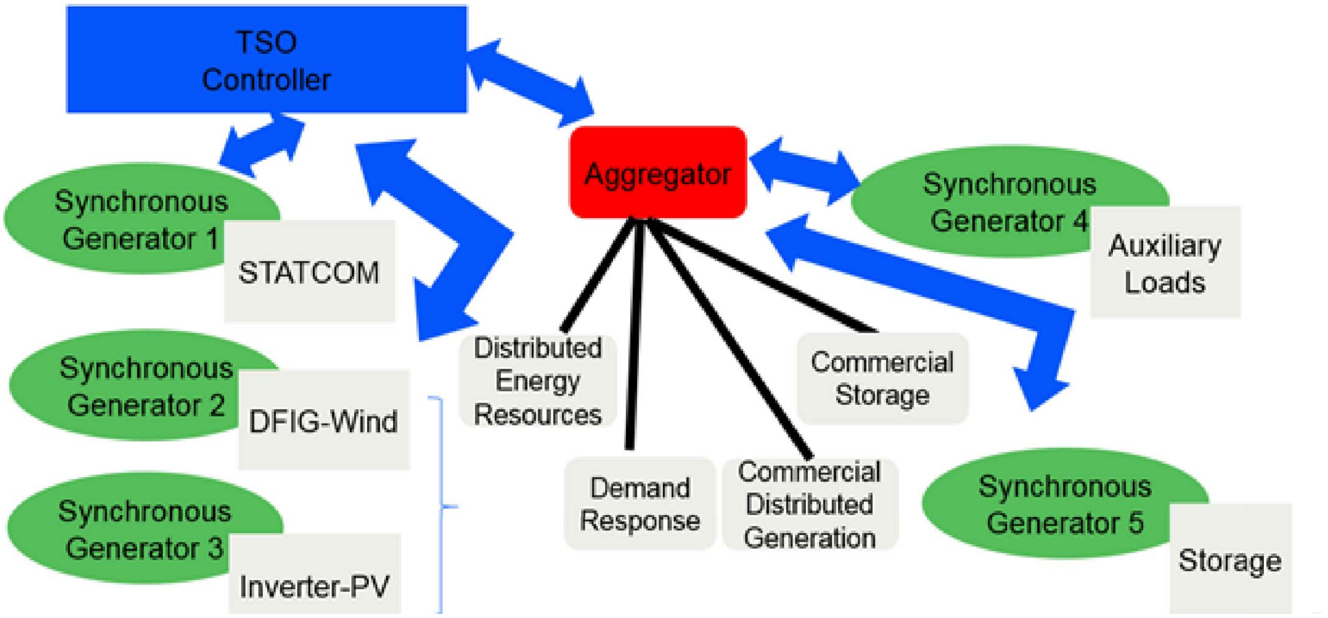

Fig. 3: Proposed architecture with improvements in the conventional synchronous generators, and using aggregator

The real and reactive power consumed by auxiliary loads is actually an interpretative burden on conventional generators, and this can further limit the reactive power provision by generators. With double-peaker CCGT, this provision can be made flexible, and it can be utilized as a component in the proposed architecture.

Aggregators have access to customers as demand response, and distributed energy resources. Commercial entities as distributed generators, and storage facilities can also take part in this aggregation. Storage and parasitic loads at generating units can offer flexibility to aggregators, and thus the aggregators have a range of reactive power options from customers, third party entities, and generators. The aggregators can thus offer flexibility to TSO for solving reactive power management issues at TSO, other than asking conventional generators only for the reactive power provision.

Aggregator has built-in intelligence to take decisions based on the inputs from these participants. These decisions are dependent on data, cash flow (cost-benefit analysis), availability of reactive power etc. There will be optimization tools inside the aggregator to serve this purpose. The aggregator then generates a flexibility curve in order to provide services to TSO. This flexibility will depend on the remunerating price, capacity, time of requirement, and the place of required service. The TSO controller can take decisions based on information in Table 1.

### FLEXIBILITY OFFERED BY AUXILIARY LOADS

For the design of a power plant, there are some loads (parasitic) to be operated for the functionality of plant. These loads are not intended in terms of net power generation. Thus, these are auxiliary loads, and require auxiliary power to support the power plant.These auxiliary services are not only needed for transient states, start-up, shutdown, and fault conditions, but also for the operation of power plant during the normal conditions [13].

However, these auxiliaries constitute a non-negligible part of power generated by the plant. According to EPRI (Electric Power Research Institute), 4.6% energy generated is wasted in auxiliary services [14]. It also depends on the type of fuel; Coal-based power plants utilize 5-8% of generating capacity, while CCGT (Combined Cycle Gas Turbine) power plants utilize 2-5% of generating capacity [15]. These auxiliaries are designed under the consideration of size of load to be served, and the degree of service continuity [13]. The conventional plants usually have loads like boiler feed pump, compressor, cooling tower, water treatment system, air conditioning system, generation step-up transformer etc. [15].

These loads also depend on the type of technology used by the power plant. For example, a combined cycle power plant includes additional loads like dampers, and shutdown diesel generator. It may also include fire protection system, continuous emission monitoring system, unit transformers etc. [16].

Combined cycle power plants (CCPP) have high efficiency than coal and nuclear plants, and therefore they have low auxiliary power consumption. However, the rate of load change (in load follow mode) is low for high loading, and nuclear appears as a better option there. For low loading, CCPP works better than nuclear, and coal [17]. Particularly in Italy, with unavailability of nuclear power plants, the competition is amongst coal and CCGT (Combined Cycle Gas Turbine). At high capacity factor, coal is cheaper than CCGT, and the reverse is true in vice versa [18]. It therefore indicates coal to be used as base load. However, with the abundance of renewable resources in Italy, the base load is provided by these renewables (with zero fuel cost). Coal serves the purpose of intermediate loading, and CCGT plants are used as double-peaker power plants.

These peaker power plants run only when there is an increase in demand, and usually Italy has two peaks for energy requirement per day. Due to not only cost, but also flexibility, that makes CCGT a better option. For a hot start-up (time to start-up following shutdown within 8 hours), the time taken by CCGT plant is 30-60 minutes, as opposed to 80-150 minutes by coal based power plants. CCGT plants also have high start-up reliability (around 95-99%), as opposed to 87-93% by coal based power plants [17].

## V. CONCLUSION

Current Italian regulations allow TSO to get reactive power services from conventional generating units only. However, there are limitations, which needs improvement at the conventional plants. The proposed architecture discusses the improvements at the conventional coal and combined cycle power plants, and the involvement of aggregated virtual power plants for the provision of further flexibility in the reactive power management. As an extension, the architecture should take into account other ancillary services too.

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Table 1 : Flexibility to TSO

| Source of Reactive Power | Costs | Flexibility to TSO |
|---|---|---|
| Synchronous generators with STATCOM | High capital costs are required to install STATCOMs at conventional power plants. However, the operating costs are moderate for controllers and maintenance. | Added flexibility to conventional power plants, by producing reactive power without compromising with real power. |
| Synchronous generators with DFIG based windfarms,i.e. AC-DC-AC converters OR conventional PV inverters | Capital costs are low considering that the wind farms are already in place, and the costs of converters are only to be considered. The operating costs are moderate for controllers and maintenance. | Flexibility to be achieved by oversizing the converters. The margin of flexibility is low when the converters operate at zero or very low real power(no/very less wind, and during night). |
| Synchronous generators with auxiliary loads | There are no capital costs considering that the double peaker auxiliary combined cycle plants are already in place. Operating costs are the fuel, and maintenance costs. | Flexibility to be achieved by using hot start-up. It is dependant on size of peaker plants. |
| Synchronous generators with storage | Battery related costs. | Flexibility is dependant on battery sizing. |
| Aggregators | High capital costs for the installation of DERs, DG, and storage. High capital costs for development of aggregator software platform. The operating costs are for controllers and maintenance. | New era of flexibility, with new business opportunities for all actors of power system. |

## APPENDIX: THEORETICAL VALIDATION AND FUTURE WORK

Consider a subset of the architecture in figure 3, with some assumed values in order to give a theoretical validation of the flexibility generated by the proposed method. The subset is shown in figure 4. Two scenarios are considered for the evaluation purposes. In the first scenario, the generators are the suppliers of reactive power up to Q MVAR with cost of C \$/MVAR (considered as basis of comparison). The fact that the cost for reactive power increases above a particular rating is neglected here for ease of analysis. In the second scenario, the suppliers include generators (with STATCOM), and aggregators (with demand-response capabilities).

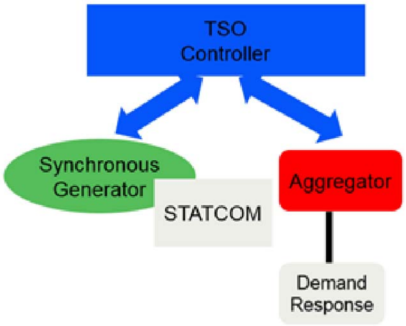

Fig. 4: Amended proposed architecture for validation

Operating costs for STATCOM are lower than generators, so the cost is assumed 0.8C \$/MVAR. The reactive power provision is taken as one-fourth of the value Q of generators. The demand-response is considered to give up to one-eighth of the provision Q as compared to generators, at a cost of 0.6C \$/MVAR (assuming the communication and other costs are high enough). Even in this small example, the TSO has the flexibility to get up to 0.375Q MVAR from aggregators and compensation devices at cost of \$(0.9*CQ) as compared to \$(CQ) for generators. Thus, a 10% cost-effectiveness is achievable with an available flexibility of 37.5%.

As a future work, the detailed architecture will be considered, and the experimental validation will be done. The detailed models with the exact parameters for the components will be taken, and the hardware will be integrated with simulation tools in order to perform real-time simulations. Other ancillary services will be concatenated in order to generate an overall picture for flexibility and efficiency analysis.

Exact cost analysis, with an emphasis on ICT deployment, and communication protocols will be evaluated too. Implementations in other European countries will be focused, and their architectures will be studied and analyzed with respect to implementations in line with the proposed architecture.

## REFERENCES

[1] P. W. Sauer. (2003, Sep.) What is reactive power? Dept. Elect. and Comp. Eng., University of Illinois at Urbana-Champaign. [Online]. Available: http://pserc.wisc.edu/documents/publications/special_interest_publications/grid_reliability/

[2] J. Parmar. (2011) Importance of reactive power for system. [Online]. Available: https://electricalnotes.wordpress.com/2011/03/21/importance-of-reactive-power-for-system/

[3] H. Saadat, *Power System Analysis*, 3rd ed. USA: McGraw Hill, 2002.

[4] "Payment for reactive power," Federal Energy Regulatory Commission, Tech. Rep. AD14-7, 2014.

[5] A. Ellis, R. Nelson, E. V. Engeln, R. Walling, J. MacDowell, L. Casey, E. Seymour, W. Peter, C. Barker, B. Kirby, and J. R. Williams, "Reactive power performance requirements for wind and solar plants," in *Proc. IEEE Power and Energy Society General Meeting '2012*, San Diego, CA, USA, 22–26, 2012.

[6] Deliberation number 111/06. Authority for Electric Energy, Gas and Hydro Services. [Online]. Available: http://www.autorita.energia.it/it/inglese/index.htm

[7] Grid code. Terna. [Online]. Available: https://www.terna.it/en-gb/sistemaelettrico/codicedirete.aspx

[8] Document 354/13. AEEGSI.

[9] Document 298/16. AEEGSI.

[10] (2015) Towards smarter grids: Developing tso and dso roles and interactions for the benefit of consumers. european network of transmission system operators for electricity. [Online]. Available: https://www.entsoe.eu/publications/position-papers/position-papers-archive/Pages/Position-Papers/Position-Paper-on-TSO-DSO-interactions.aspx

[11] (2010) The role of distribution system operators (dsos) as information hubs. Union of the Electricity Industry - EURELECTRIC. [Online]. Available: http://www.eurelectric.org/media/44143/role_of_dsos_as_information_hubs_final_draft_10-06-10-2010-200-0001-01-e.pdf

[12] F. Pilo, G. Mauri, B. BakJensen, E. Kampf, J. Taylor, and F. Silvestro, "Control and automation functions at the tso and dso interface - impact on network planning," in *Proc. CIRED International Conference on Electricity Distribution*, Galsgow, UK, 2017.

[13] I. Kuzle, D. Bosnjak, and H. Pandzi, "Auxiliary system load schemes in large thermal and nuclear power plants," in *Proc. International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids*, Dubrovnik, Croatia, May 2010.

[14] "Program on technology innovation: Electricity use in the electric sector. opportunities to enhance electric energy efficiency in the production and delivery of electricity," Electric Power Research Institute, Tech. Rep. 1024651, Nov. 2011.

[15] T. N. Raval and D. R. N. Patel, "Optimization of auxiliary power consumption of combined cycle power plant," in *Proc. Nirma University International Conference on Chemical, Civil and Mechanical Engineering Tracks NUiCONE.*

[16] M. Alyah, J. Ashman, A. Arisoy, E. Astley, E. Herbst, P. Jennings, A. Gusev, R. Emelyanov, and R. Radevsky, "Combined cycle power plants," in *IMIA Annual Conference*, Mexico, Sep. 2015.

[17] L. Balling, "Flexible future for combined cycle," Modern Power Systems, pp. 61–65, dec 2010.

[18] G. M. Masters, *Renewable and Efficient Electric Power Systems*, 2nd ed. USA: WILEY, 2013.