Literature Survey of Security Constrained Optimal Power Flow (SCOPF) and Contingency Preventive/Corrective Control

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One of the very first studies of SCOPF and corrective control was performed by **Monticelli** et al. back in 1987 [1]. The paper was cited almost 300 times by both classical and modern authors. This survey is aimed to illustrate how the topic evolved.

The methodology is based on citation mapping. The papers that cited [1] are depicted as the first generation. Then, the second generation of papers that cited the first generation is introduced and so on. The process is depicted in Fig. 1. Only two generations of papers are considered in the survey because of the unreasonably large generation three.

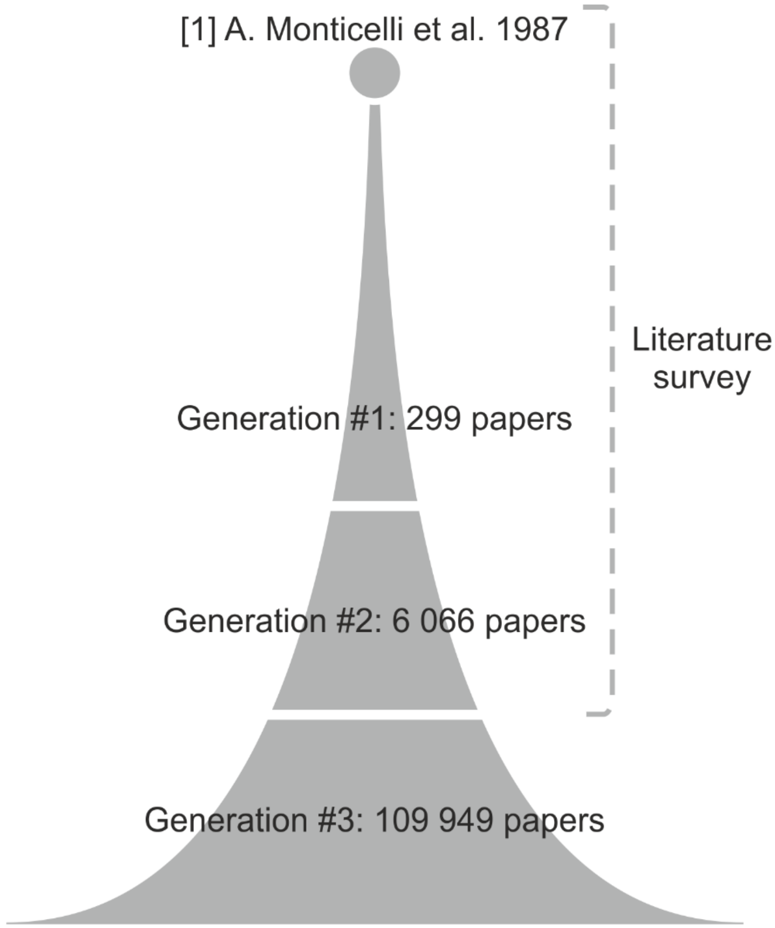

Fig. 1. Citation mapping methodology.

Citation mapping was composed using Scopus database and Gephi software (Fig. 2). Since some citations refer to the same papers, the total number of nodes (papers) reach 4474, the number of edges (citations) - 6365.

The Gephi algorithm tries to stretch out the citation network. Thus, the most interconnected and relevant nodes remain close to the center. Since [1] is the reference point of the network, the paper of Monticelli stands in the core. Less interconnected nodes tend to the perimeter of the network. The size of nodes set proportional to the total number of citations. There exist several highly cited papers far from the center of the network. This means that the papers are popular, but not strongly interconnected with the considered topic.

The interactive version of the citation network is available at http://andreychurkin.ru/materials/network1/

[1] A. Monticelli, M. V. F. Pereira, and S. Granville, "Security-constrained optimal power flow with post-contingency corrective rescheduling," *IEEE Trans. Power Syst.*, 1987.

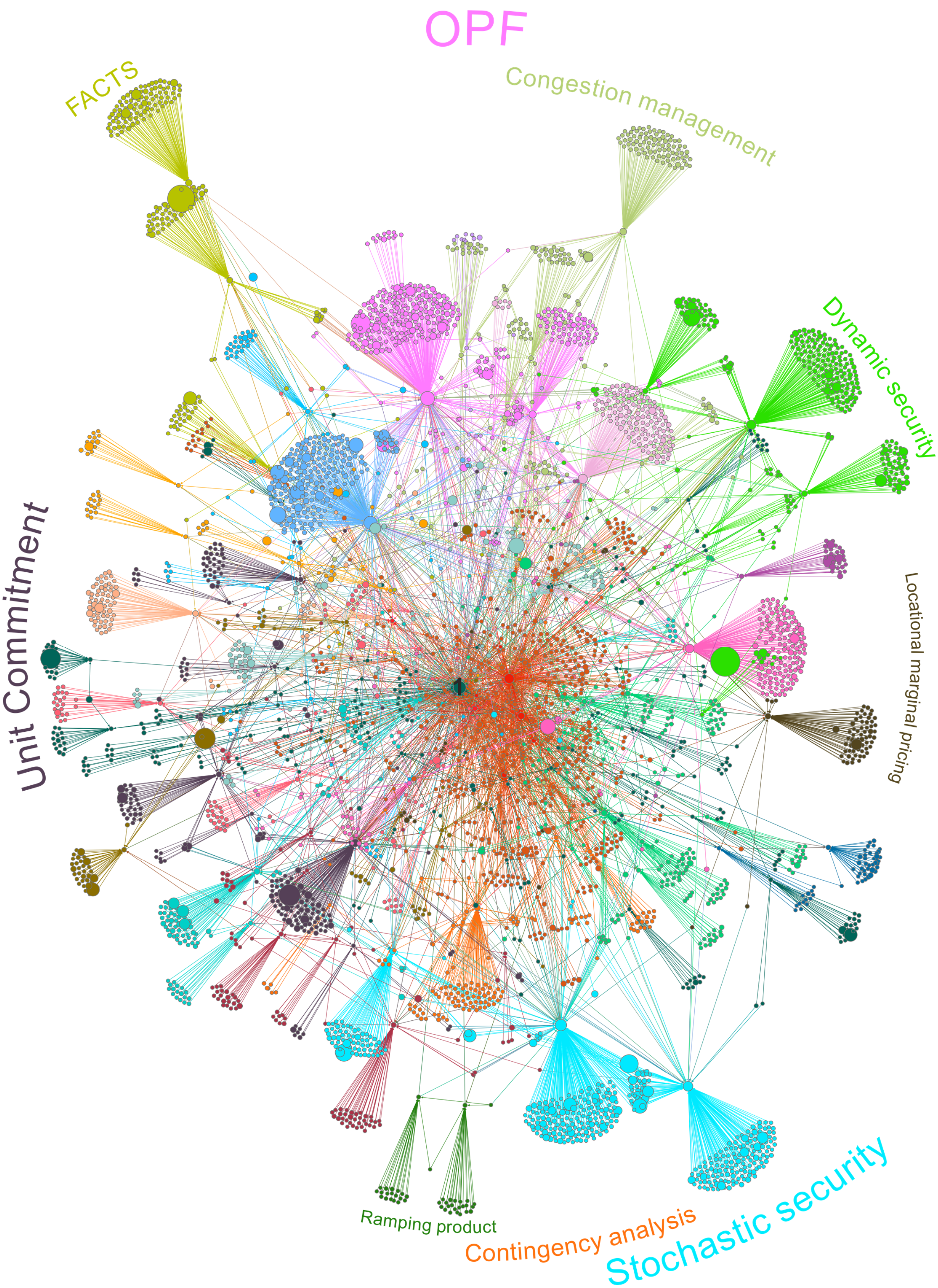

Fig. 2. Citation network of Monticelli et al. [1].

The nodes are colored using Gephi modularity algorithm that allows identification of related studies. The survey first considers several important sections of the citation network, revealing the neighboring fields and research directions. Then, the core of the network is considered with the most relevant papers to the SCOPF research.

Section 1: Stochastic security & Contingency analysis

The papers grouped in Section 1 mostly address the stochastic (probabilistic) analysis of power systems operation and planning. Contingency analysis, as part of SCOPF, was also studied by numerous authors of the section. The main motivation of this research direction – uncertainty of renewable generation and its influence on power system security. The detailed section scheme with the key publications is given in Fig. 3.

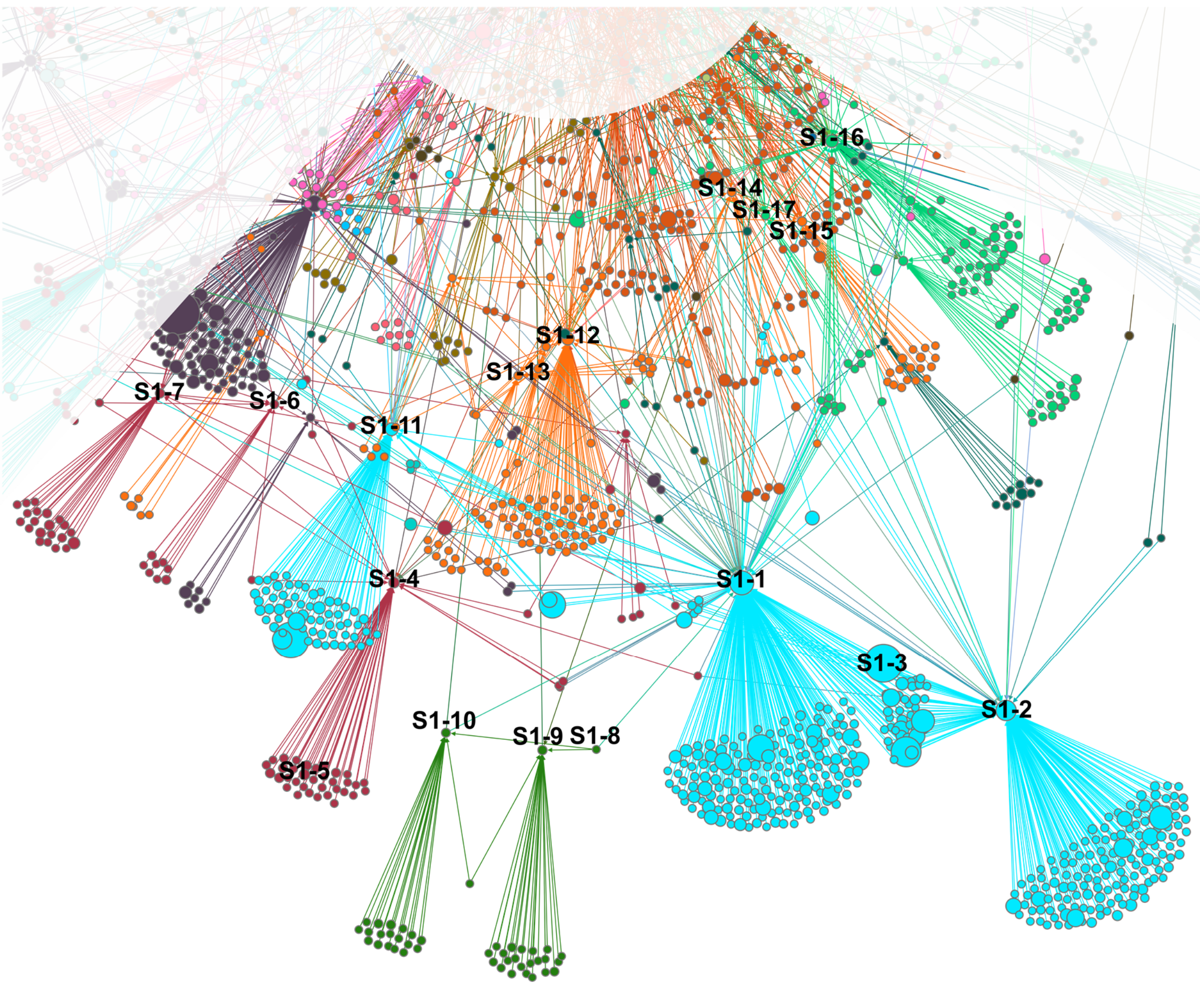

Fig. 3. Section 1 of the citation network.

The significant blue bunches at the bottom represent the heritage of professors F. Bouffard and F.D. Galiana. In [S1-1] the market-clearing problem with stochastic security was introduced. It was stated that compared to deterministic SCOPF, stochastic SCOPF could decrease the incremental cost of reserve and energy. In [S1-2] practices of market clearing, reserves scheduling, primary, secondary, and tertiary control were considered. The simultaneous optimization of the aforementioned services was suggested. Stochastic security and market clearing in the presence of significant wind generation are studied in [S1-3]. Most of the papers connected to [S1-1, 2, 3] focus on a stochastic optimization of market clearing and unit commitment that is justified by intermittent renewable generation.

The red bunches of papers to the left focus on computational issues of OPF and unit commitment in stochastic formulation [S1-4, 5, 6, 7]. The papers of the green bunches [S1-8, 9, 10] elaborate on the idea of ramping market (ramp product) development. The blue bunch originated by [S1-11] contains studies of security aspects of power systems operation.

The orange groups of papers in the middle of the section study SCOPF and contingency analysis. S. Fliscounakis et al. [S1-12] developed an algorithm for contingencies ranking with respect to uncertainty, preventive, and corrective actions. The papers related to the studies of M. Majidi-Qadikolai and R. Baldick [S1-13] and [S1-14] elaborate on transmission expansion planning incorporating contingency analysis. R. Moreno et al. [S1-15] also focus on probabilistic transmission expansion planning with security and corrective control. J. Condren et al. [S1-16] introduced the term expected-security-cost optimal power flow and studied maximization of the expected value of social welfare in a probabilistic sense. The related green group of papers such as [S1-17] also examine stochastic optimal dispatch formulations with security constraints.

[S1-1] F. Bouffard, F. D. Galiana, and A. J. Conejo, "Market-clearing with stochastic security - Part I: Formulation," *IEEE Trans. Power Syst.*, 2005.

[S1-2] F. D. Galiana, F. Bouffard, J. M. Arroyo, and J. F. Restrepo, "Scheduling and pricing of coupled energy and primary, secondary, and tertiary reserves," Proc. IEEE, 2005.

[S1-3] F. Bouffard and F. D. Galiana, "Stochastic security for operations planning with significant wind power generation," IEEE Trans. Power Syst., 2008.

[S1-4] A. Papavasiliou, S. S. Oren, and B. Rountree, "Applying High Performance Computing to Transmission-Constrained Stochastic Unit Commitment for Renewable Energy Integration," IEEE Trans. Power Syst., 2015.

[S1-5] M. Lubin, Y. Dvorkin, and S. Backhaus, "A Robust Approach to Chance Constrained Optimal Power Flow with Renewable Generation," IEEE Trans. Power Syst., 2016.

[S1-6] A. Papavasiliou and S. S. Oren, "A comparative study of stochastic unit commitment and security-constrained unit commitment using high performance computing," 2018.

[S1-7] D. M. Falcão, "High performance computing in power system applications," in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 1997.

[S1-8] E. Heydarian-Forushani, M. E. H. Golshan, M. Shafie-Khah, and P. Siano, "Optimal Operation of Emerging Flexible Resources Considering Sub-Hourly Flexible Ramp Product," IEEE Trans. Sustain. Energy, 2018.

[S1-9] C. Wu, G. Hug, and S. Kar, "Risk-Limiting Economic Dispatch for Electricity Markets with Flexible Ramping Products," IEEE Trans. Power Syst., 2016.

[S1-10] E. Moiseeva, M. R. Hesamzadeh, and D. R. Biggar, "Exercise of Market Power on Ramp Rate in Wind-Integrated Power Systems," IEEE Trans. Power Syst., 2015.

[S1-11] M. Shahidehpour, W. F. Tinney, and Y. Fu, "Impact of security on power systems operation," in Proceedings of the IEEE, 2005.

[S1-12] S. Fliscounakis, P. Panciatici, F. Capitanescu, and L. Wehenkel, "Contingency ranking with respect to overloads in very large power systems taking into account uncertainty, preventive, and corrective actions," IEEE Trans. Power Syst., 2013.

[S1-13] M. Majidi-Qadikolai and R. Baldick, "Stochastic Transmission Capacity Expansion Planning with Special Scenario Selection for Integrating n-1 Contingency Analysis," IEEE Trans. Power Syst., 2016.

[S1-14] M. Majidi-Qadikolai and R. Baldick, "Integration of N-1 contingency analysis with systematic transmission capacity expansion planning: ERCOT case study," IEEE Trans. Power Syst., 2016.

[S1-15] R. Moreno, D. Pudjianto, and G. Strbac, "Transmission network investment with probabilistic security and corrective control," IEEE Trans. Power Syst., 2013.

[S1-16] J. Condren, T. W. Gedra, and P. Damrongkulkamjorn, "Optimal power flow with expected security costs," IEEE Trans. Power Syst., 2006.

[S1-17] C. E. Murillo-Sánchez, R. D. Zimmerman, C. L. Anderson, and R. J. Thomas, "A stochastic, contingency-based security-constrained optimal power flow for the procurement of energy and distributed reserve," Decis. Support Syst., 2013.

Section 2: Locational marginal pricing

The relatively small section of the citation network features studies of LMP clearing mechanism design and calculations.

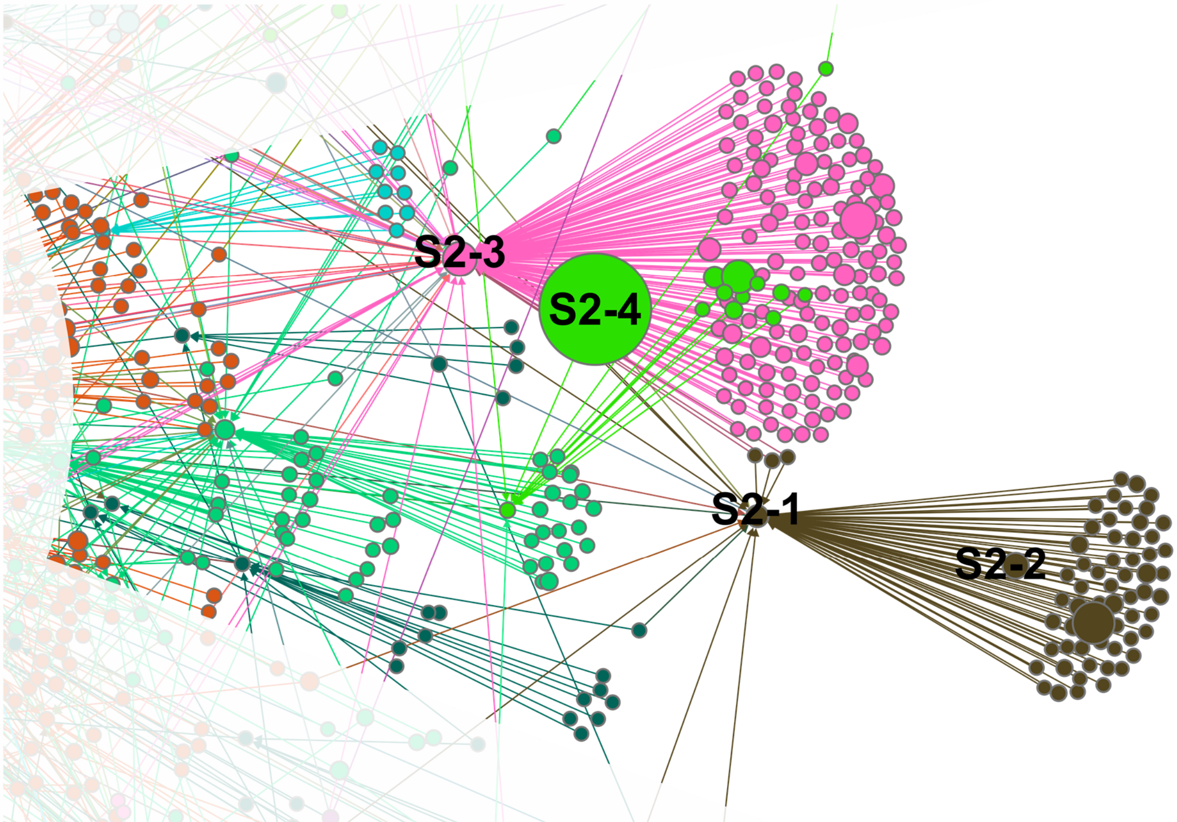

Fig. 4. Section 2 of the citation network.

The review paper of E. Litvinov [S2-1] set the pace for the related studies colored brown. Many of the LMP market studies exploit stochastic analysis similar to Section 1 papers [S2-2]. The neighboring pink bunch of papers relates to the study of T. J. Overbye et al. [S2-3]. A comparison between AC and DC power flow models for LMP calculations was performed. Contingency analysis and SCOPF were also studied.

The giant node [S2-4] represent the paper of G. Strbac dedicated to demand side management. The topic of load control is studied by the surrounding green nodes and some other papers throughout the citation network.

[S2-1] E. Litvinov, "Design and operation of the locational marginal prices-based electricity markets," IET Gener. Transm. Distrib., 2010.

[S2-2] A. Botterud et al., "Wind power trading under uncertainty in LMP markets," IEEE Trans. Power Syst., 2012.

[S2-3] T. J. Overbye, Xu Cheng, and Yan Sun, "A comparison of the AC and DC power flow models for LMP calculations," 2004.

[S2-4] G. Strbac, "Demand side management: Benefits and challenges," Energy Policy, 2008.

Section 3: Dynamic security

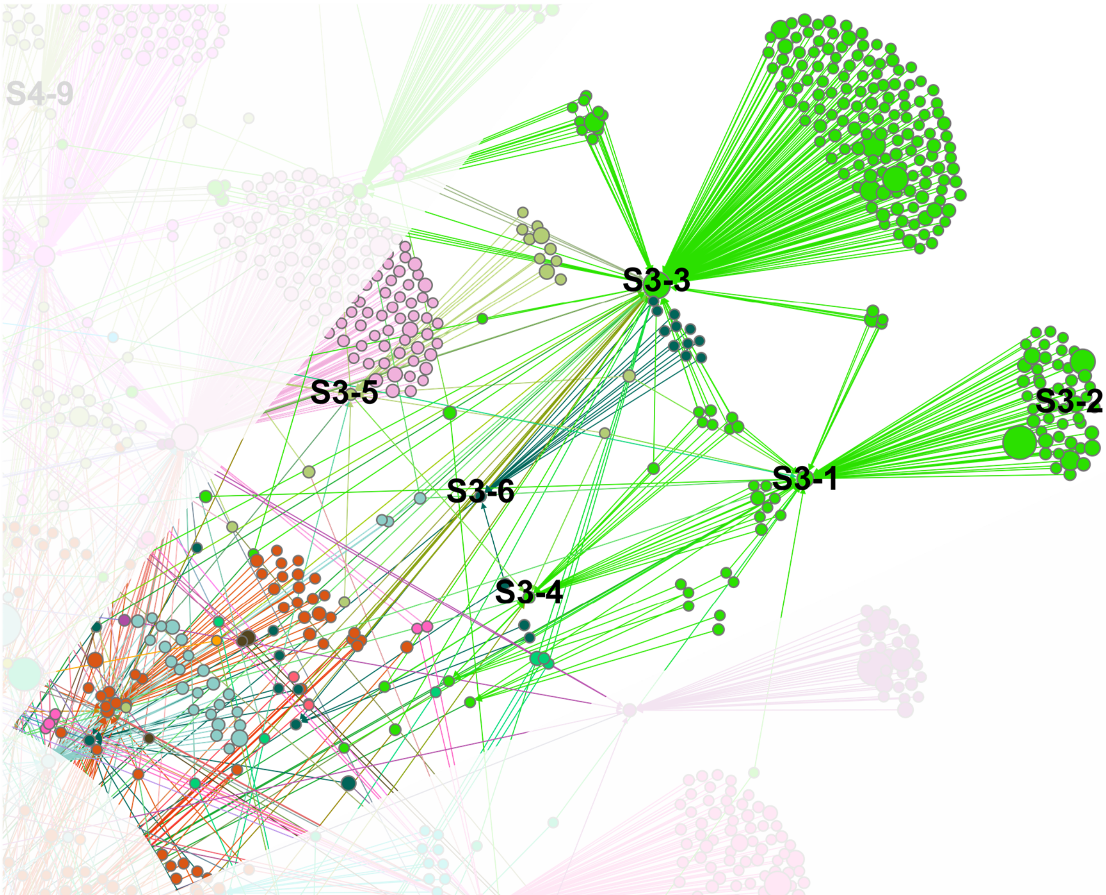

Fig. 5. Section 3 of the citation network.

The authors of this section study dynamic security of power systems. The work of D. Kuo and A. Bose [S3-1] suggested generation rescheduling method for dynamic security enhancement. The related studies such as [S3-2] analyze dynamic security and its influence on the optimal power flow. The neighboring green bunch of studies connected to [S3-3] also struggle with no nonlinear problem of OPF with transient stability constraints. The studies such as [S3-4] and [S3-5] suggest preventive control methods considering N-1 security constraints, dynamic security, and generation rescheduling. D. Wang et al. [S3-6] compared performances of centralized and decentralized model predictive control.

[S3-1] D. H. Kuo and A. Bose, "A generation rescheduling method to increase the dynamic security of power systems," IEEE Trans. Power Syst., 1995.

[S3-2] A. Pizano-Martíanez, C. R. Fuerte-Esquivel, and D. Ruiz-Vega, "Global transient stability-constrained optimal power flow using an OMIB reference trajectory," IEEE Trans. Power Syst., 2010.

[S3-3] L. Chen, Y. Tada, H. Okamoto, R. Tanabe, and A. Ono, "Optimal operation solutions of power systems with transient stability constraints," IEEE Trans. Circuits Syst. I Fundam. Theory Appl., 2001.

[S3-4] D. Gan, Z. Qu, H. Cai, and X. Wang, "Methodology and computer package for generation rescheduling," IEE Proc. - Gener. Transm. Distrib., 2002.

[S3-5] M. K. Maharana and K. S. Swarup, "Graph theoretic approach for preventive control of power systems," Int. J. Electr. Power Energy Syst., 2010.

[S3-6] D. Wang, M. Glavic, and L. Wehenkel, "Comparison of centralized, distributed and hierarchical model predictive control schemes for electromechanical oscillations damping in large-scale power systems," Int. J. Electr. Power Energy Syst., 2014.

Section 4: OPF, Congestion management, FACTS for security

Much effort has been made in the direction of OPF calculation. Different approaches and techniques are briefly discussed in the section.

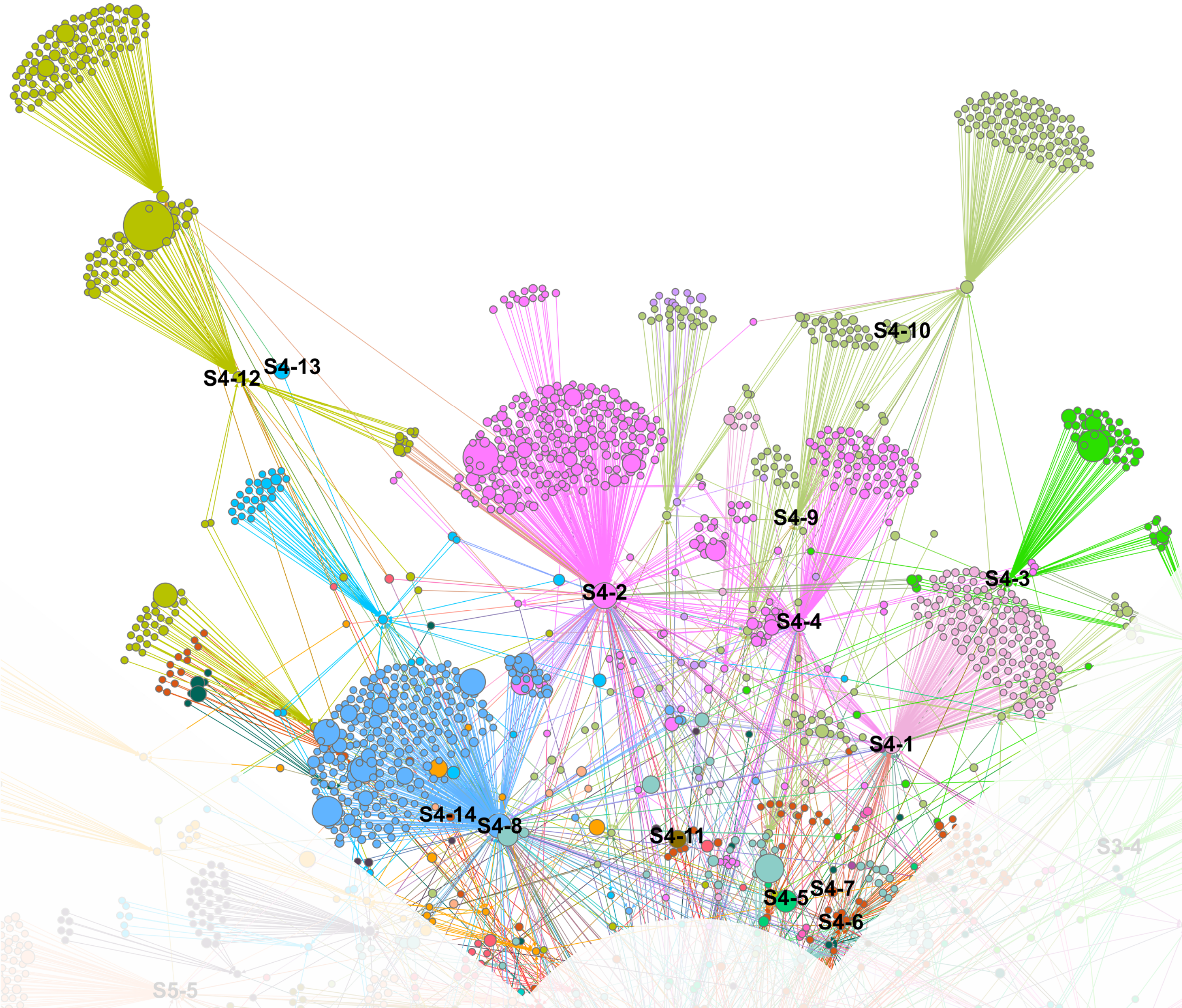

Fig. 6. Section 4 of the citation network.

In order to systemize the knowledge of OPF calculations, numerous literature surveys have been written [S4-1], [S4-2]. The variety of neighboring bunches represent different approaches to OPF calculation. L. Cherf et al. [S4-3] applied the mean field theory for OPF involving continuous and discrete variables. Numerous OPF studies such as [S4-4] exploited heuristic algorithms. S. Low [S4-5] summarized convex relaxation techniques for the OPF problem. F. Capitanescu and L. Wehenkel [S4-6] experimented with the interior-point method for solving large scale OPF and SCOPF. A survey of distributed optimization and control algorithms is given in [S4-7]. The large blue bunch of papers connected to [S4-8] also elaborates on both linear and nonlinear OPF problems.

The close research direction focuses on congestion management problems. H. Yamina and S. Shahidehpour [S4-9] suggested coordination scheme between generation companies and the system operator for congestion management. S. Dutta and S. Singh [S4-10] exploited the Particle Swarm Optimization algorithm to optimize congestion management. Many of the related papers applied heuristic methods to congestion management problems considering line overloads and voltage limits. The bibliographical survey [S4-11] presents different approaches to congestion management issues in deregulated electricity markets.

Another distinguishable class of studies focuses on OPF and congestion management considering FACTS devices. G.N. Taranto et al. [S4-12] described a methodology of FACTS devices representation in OPF models. Studies like [S4-13] consider locating FACTS for congestion management. Optimization of FACTS corrective control has been studied in [S4-14].

[S4-1] S. Frank, I. Steponavice, and S. Rebennack, "Optimal power flow: A bibliographic survey I Formulations and deterministic methods," Energy Systems. 2012.

[S4-2] M. Huneault and F. D. Galiana, "A Survey Of The Optimal Power Flow," IEEE Trans. Power Syst., 1991.

[S4-3] L. Cherf, H. Suzuki, and K. Katou, "Mean field theory for optimal power flow," IEEE Trans. Power Syst., 1997.

[S4-4] D. Devaraj and B. Yegnanarayana, "Genetic-algorithm-based optimal power flow for security enhancement," IEE Proc. - Gener. Transm. Distrib., 2005.

[S4-5] S. H. Low, "Convex relaxation of optimal power flow - Part i: Formulations and equivalence," IEEE Trans. Control Netw. Syst., 2014.

[S4-6] F. Capitanescu and L. Wehenkel, "Experiments with the interior-point method for solving large scale Optimal Power Flow problems," Electr. Power Syst. Res., 2013.

[S4-7] D. K. Molzahn et al., "A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems," IEEE Transactions on Smart Grid. 2017.

[S4-8] O. Alsaç, J. Bright, M. Prais, and B. Stott, "Further developments in lp-based optimal power flow," IEEE Trans. Power Syst., 1990.

[S4-9] H. Y. Yamina and S. M. Shahidehpour, "Congestion management coordination in the deregulated power market," Electr. Power Syst. Res., 2003.

[S4-10] S. Dutta and S. P. Singh, "Optimal rescheduling of generators for congestion management based on particle swarm optimization," IEEE Trans. Power Syst., 2008.

[S4-11] A. Kumar, S. C. Srivastava, and S. N. Singh, "Congestion management in competitive power market: A bibliographical survey," Electr. Power Syst. Res., 2005.

[S4-12] G. N. Taranto, L. V. G. Pinto, and M. V. F. Pereira, "Representation of FACTS devices in power system economic dispatch," IEEE Trans. Power Syst., 1992.

[S4-13] N. Acharya and N. Mithulananthan, "Locating series FACTS devices for congestion management in deregulated electricity markets," Electr. Power Syst. Res., 2007.

[S4-14] M. Sahraei-Ardakani and K. W. Hedman, "Day-Ahead Corrective Adjustment of FACTS Reactance: A Linear Programming Approach," IEEE Trans. Power Syst., 2016.

Section 5: Unit Commitment

The wide range of papers on the left side of the citation network can be categorized as unit commitment research.

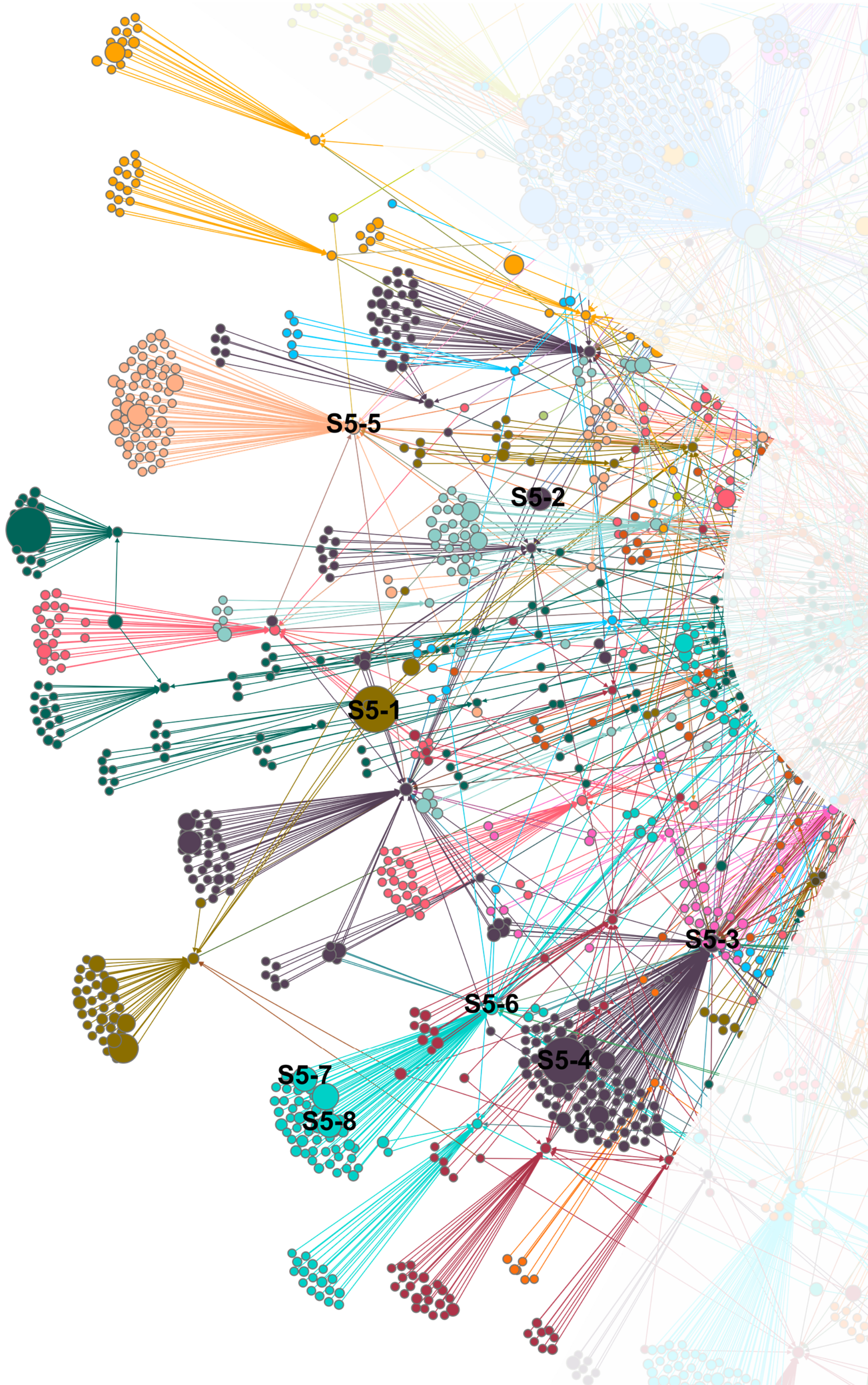

Fig. 7. Section 5 of the citation network.

The giant brown node [S5-1] represents a bibliographical survey of unit commitment done by N.P. Padhy. Security-constrained unit commitment with AC modeling is studied in [S5-2, 3, 4]. It is worth highlighting professor M. Shahidehpour, who has contributed to numerous papers of this section. The papers connected to [S5-5] study optimal generation scheduling with security constraints. In the blue bunch of papers [S5-6, 7, 8], switching actions are considered as a tool for power flow optimization and security enhancement.

[S5-1] N. P. Padhy, "Unit commitment - A bibliographical survey," IEEE Trans. Power Syst., 2004.

[S5-2] Y. Fu, M. Shahidehpour, and Z. Li, "Security-constrained unit commitment with AC constraints," IEEE Trans. Power Syst., 2005.

[S5-3] Y. Fu, M. Shahidehpour, and Z. Li, "AC contingency dispatch based on security-constrained unit commitment," IEEE Trans. Power Syst., 2006.

[S5-4] J. Wang, M. Shahidehpour, and Z. Li, "Security-constrained unit commitment with volatile wind power generation," IEEE Trans. Power Syst., 2008.

[S5-5] H. Yamin, S. Al-Agtash, and M. Shahidehpour, "Security-constrained optimal generation scheduling for GENCOs," IEEE Trans. Power Syst., 2004.

[S5-6] G. Schnyder and H. Glavitsch, "Security Enhancement Using An Optimal Switching Power Flow," IEEE Trans. Power Syst., 1990.

[S5-7] K. W. Hedman, M. C. Ferris, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," IEEE Trans. Power Syst., 2010.

[S5-8] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," IEEE Trans. Power Syst., 2009.

The core: SCOPF

The previous five sections outlined the main research directions connected to the SCOPF problem. The center of the citation network contains the most relevant studies of SCOPF.

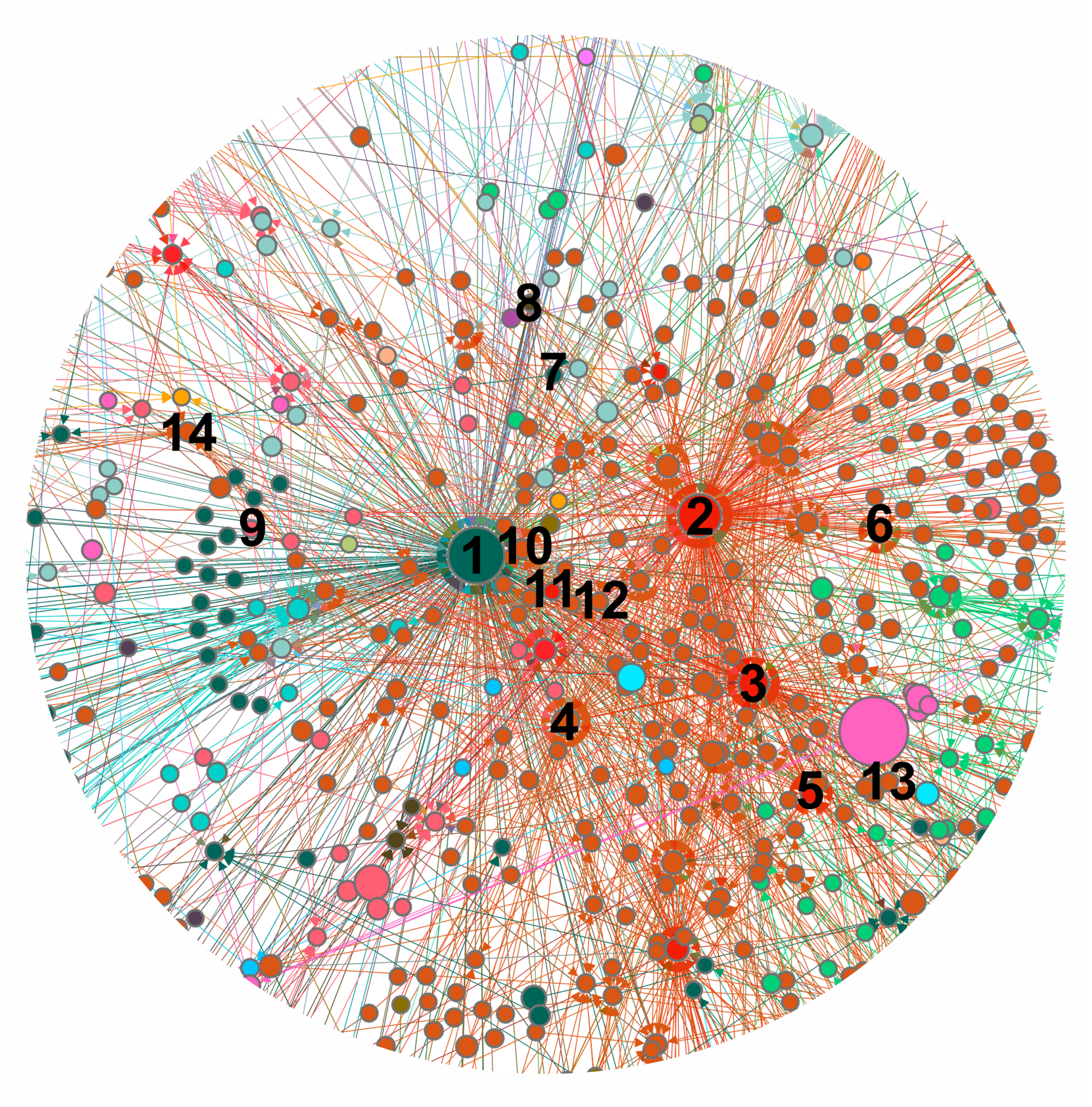

Fig. 8. The core the citation network.

It is worth mentioning the contribution made by F. Capitanescu, who published tens of papers focused on SCOPF problems and corrective control. Almost all of his papers are closely related to the initial study of Monticelli [1] and, therefore, are located in the center of the citation network. In the review paper [2], F. Capitanescu et al. describe the main challenges to SCOPF research. In the section "Beyond the classical SCOPF formulations," the authors formulate future developments such as multistage stochastic programming approach. In [3], contingency filtering techniques for preventive SCOPF were implemented to speed up the calculations. An iterative approach for corrective SCOPF using contingency filtering and Benders decomposition was suggested in [4].

A series of studies considered preventive-corrective SCOPF and dynamic security. Xu et al. [5] suggested optimization of both preventive and corrective SCOPF actions using a hybrid computational strategy that combines evolutionary algorithm and interior-point method. F. Capitanescu et al. [6] proposed an approach for coupling SCOPF optimization and dynamic simulation. The study presents an algorithm for preventive/corrective actions coordination taking into account voltage stability.

Several recent papers incorporated closed-loop approaches, decentralized optimization, and frequency control into SCOPF formulation. N. Mazzi et al. [7] proposed a closed-loop algorithm for contingency alleviation that exploits network as a natural solver of power flow equations. The algorithm only needs measurements from a grid to perform optimal control actions. M. Velay et al. [8] presented the ADMM-based distributed method to solve SCOPF considering the primary frequency response of generators after an incident. The new method requires no central coordination: distributedly found solutions of the SCOPF problem guarantee that an operating point exists after the disconnection of a generator, a line or even after system area separation. J. Mohammadi et al. [9] also elaborated on a distributed approach to the SCOPF problem. The problem is formulated in a multi-agent context where the distributed optimization aims to minimize the global cost of secure power system operation. The novel approach does not require sharing information on generation cost parameters and generation settings.

The works connected to the mentioned studies of F. Capitanescu and the initial paper of A. Monticelli are also located in the center of the network. They shed light on additional features of the SCOPF problem. D.T. Phan and X.A. Sun [10] proposed a new formulation for the corrective SCOPF that allows a reduction in the number of post-contingency actions and the amount of MW rescheduling. Y. Dvorkin et al. [11] studied the optimization of primary frequency response in preventive SCOPF. It was shown that optimization of generators droop coefficients could lead to cost savings and security enhancement. A contingency partitioning approach for preventive-corrective SCOPF was suggested in [12]. The idea behind this approach is to partition the contingencies intro two sets: one is secured in preventive control stage, the other - in the corrective control stage. The simulations showed that the proposed method can provide high-quality solutions with much higher computation speed. J. Cao et al. [13] studied corrective SCOPF algorithm with distributed energy storage control. G. Hug [14] suggested a multi-objective optimization of corrective control that minimizes generation cost and overall system risk probability.

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[1] A. Monticelli, M. V. F. Pereira, and S. Granville, "Security-constrained optimal power flow with post-contingency corrective rescheduling," *IEEE Trans. Power Syst.*, 1987.

[2] F. Capitanescu et al., "State-of-the-art, challenges, and future trends in security constrained optimal power flow," Electric Power Systems Research. 2011.

[3] F. Capitanescu, M. Glavic, D. Ernst, and L. Wehenkel, "Contingency filtering techniques for preventive security-constrained optimal power flow," IEEE Trans. Power Syst., 2007.

[4] F. Capitanescu and L. Wehenkel, "A new iterative approach to the corrective security-constrained optimal power flow problem," IEEE Trans. Power Syst., 2008.

[5] Y. Xu, Z. Y. Dong, R. Zhang, K. P. Wong, and M. Lai, "Solving preventive-corrective SCOPF by a hybrid computational strategy," IEEE Trans. Power Syst., 2014.

[6] F. Capitanescu, T. Van Cutsem, and L. Wehenkel, "Coupling optimization and dynamic simulation for preventive-corrective control of voltage instability," IEEE Trans. Power Syst., 2009.

[7] N. Mazzi, B. Zhang, and D. S. Kirschen, "An Online Optimization Algorithm for Alleviating Contingencies in Transmission Networks," IEEE Trans. Power Syst., 2018.

[8] M. Velay, M. Vinyals, Y. Besanger, and N. Retiere, "Fully distributed security constrained optimal power flow with primary frequency control," Int. J. Electr. Power Energy Syst., 2019.

[9] J. Mohammadi, G. Hug, and S. Kar, "Agent-based distributed security constrained optimal power flow," IEEE Trans. Smart Grid, 2018.

[10] D. T. Phan and X. A. Sun, "Minimal Impact Corrective Actions in Security-Constrained Optimal Power Flow Via Sparsity Regularization," IEEE Trans. Power Syst., 2015.

[11] Y. Dvorkin, P. Henneaux, D. S. Kirschen, and H. Pandzic, "Optimizing Primary Response in Preventive Security-Constrained Optimal Power Flow," IEEE Syst. J., 2018.

[12] Y. Xu, H. Yang, R. Zhang, Z. Y. Dong, M. Lai, and K. P. Wong, "A contingency partitioning approach for preventive-corrective security-constrained optimal power flow computation," Electr. Power Syst. Res., 2016.

[13] J. Cao, W. Du, and H. F. Wang, "An Improved Corrective Security Constrained OPF with Distributed Energy Storage," IEEE Trans. Power Syst., 2016.

[14] G. Hug, "Generation cost and system risk trade-off with corrective power flow control," in 2012 50th Annual Allerton Conference on Communication, Control, and Computing, Allerton 2012, 2012.

Conclusions

The current survey aims to highlight the most relevant papers for the SCOPF problem. It also outlines the related research directions. Even though SCOPF is a computationally hard problem itself, the researchers continue complicating it by adding more parameters into the algorithms, making them more realistic. New computational techniques and approaches are used to solve the SCOPF problems. Thus, power system optimization with security constraints remains a fruitful topic open for further contributions.