PoW Blockchain infrastructure as a novel approach to power system balancing

I. Ostheimer *, G. Horvat *, M. Vukobratović *, B. Bijelić *, Z. Balkić *
* Base58 Ltd., Systems engineering Department, Osijek, Croatia
ivan.ostheimer@base58.hr

***Abstract*—With the introduction of distributed generation, the power system faces new challenges related to the stability that may result in potential power outages and blackouts. New infrastructures, such as Blockchain Infrastructure (BCI), amplifies the impact on the power system stability by introducing significant power demand. Power system balancing techniques often include power reductions targeted at the customer side, presenting an unwanted effect for end users. Accordingly, this paper proposes a novel approach to providing power system balancing services by utilising a manageable BCI. To validate the balancing principle of BCI, research presented by this paper models BCI hardware by means of parameter identification, model proposal and scale-up to verify technical requirements for providing balancing services in the power system. By scale-up simulation and comparison with technical requirements, BCI fulfils fundamental requirements for providing balancing services. With integration of a control mechanism, a secondary, automatic frequency restoration reserve can be provided, improving power system stability and mitigating potential adverse effects of BCI's high energy usage.**

Keywords*—Blockchain infrastructure, frequency restoration reserve, modelling, power system balancing, proof of work

I. INTRODUCTION

Blockchain technology enables distributed processing, storage and verification of transactions stored and maintained in a decentralised and trustless manner. In its most represented implementation the hardware infrastructure that powers the blockchain technology implies respected power requirements in the power system and is often referred to as a power hungry infrastructure [1].

With the ongoing expansion of Blockchain Infrastructure (BCI) motivated from a financial standpoint, excessive energy consumption will present a significant challenge for the power grid. Grid operators of the future have not yet anticipated BCI as a significant market agent and today's power systems are in majority not designed for such demands. Finally, BCI motivated only by financial gains is never designed as flexible and controllable infrastructure and cannot respect the power system requirements [2].

The power system operates only in a way where there is a balance between consumption and production at each moment. Last decade, due to environmental policy and other regulatory frameworks, has brought a geographical dispersion of production and heterogeneity of technologies from which electricity is produced [3]. Distributed power generation technologies are volatile in nature and depend on the meteorological conditions of their locality, creating a burden on today's power system with volatile production on the one hand, and with volatile consumption on the other. Achieving balance in such a system is a multilayered challenge for technological readiness of a single domain. Volatility on both sides of the power system equation leading to instability needs to be balanced. As the volatility of generation cannot be managed, introducing a controllable consumer would benefit the stability of the power system as a whole. With that in mind, emergence of a fully controllable BCI could not only reduce the possible adverse effects on the power system that this technology has so far, but can also improve the overall stability of the power system and benefit all included parties [4].

This paper analyses the applicability of a power demanding BCI hardware for providing balancing service in the power system. Applicability is observed within the secondary (Automatic Frequency Restoration Reserve - aFRR) and tertiary (Manual Frequency Restoration Reserve - mFRR) frequency restoration reserves by modelling power profiles of blockchain hardware units.

The rest of the paper is organised as follows: Section II describes the paradigm shift in power systems with volatile production and consumption alongside with the challenges and current solutions for ensuring stability of the system; Section III proposes a solution based on BCI, that is modelled, scaled and verified in Sections IV and V respectively; Section VI gives conclusions and guidelines for future work.

II. NEW LANDSCAPE OF POWER SYSTEMS

The electric power system has had an unified development since its inception, and energy has had a one-way direction flow, from producers through transmission lines to distribution, to end users, i.e. consumers. The big and centralised producers were placed remotely from users and populated areas due to the need for a large space of the power plants, reserve or availability of primary energy source or pollution concerns in modern days [**?**]. This architecture of the power system has been undergoing radical changes for the last 15 years due to the increasing integration of Renewable Energy Sources (RES) and Distributed Generation (DG) [5]. Power production became more versatile, diverse, decentralised and geographically dispersed with multiple technologies in hand, each according to its limitations and possibilities. Such development resulted in new challenges for the power system that can be combined in two groups.

The first group is the system-wide, large-scale production of electricity from RES. Such production is not constant, and it is volatile in nature (solar and wind power plants) [6]. Large-scale RES production identifies a need for more active management requirements, considering energy production and the entire power system management in real time. Losses of the stability and decreases in security of supply are outgrowing conventional production capabilities, which have so far been responsible for the proper operation of the power system.

Second group is the integration of small-scale, intermittent, RES units on the consumer side i.e. in the distribution network. The power system has so far been essentially strictly divided into production and the consumption parts of the system, but nowadays the border has vanished and production exists throughout the power system and on multiple levels. Integration of RES into the distribution network brings challenges such as reverse power flows and problems with rated voltages at nodes with DG [7]. Continued integration of RES into the power system is inevitable due to the need to meet the European Green Deal, but also the global plan to reduce CO2 emissions, and the final transition to a CO2-neutral economy. But the challenges and unpredictability that come with it are slowly looming today.

A. *POWER SYSTEM STABILITY AND MODERN CHALLENGES*

Due to the new operating landscape, the stability of the power system is at risk. Stability and security of supply primarily depend on the balance of production and consumption at any moment in the power system:

$$\sum_{i=1}^{N} S_{N,P} = \sum_{i=1}^{M} S_{M,C} + \sum_{i=1}^{P} S_{P,L} \tag{1}$$

where $S_{N,P}$ is complex power of N number of production units P, $S_{M,C}$ is complex power of M-number of consumers C, $S_{P,L}$ is complex power of P-number of branches with losses L.

With the emergence of active distribution grids with distributed generation, large-scale RES with volatile production and unmanageable power supply, the management and stability of the power system has come into question. Consequently, how to address the challenges in volatile production and, at the same time, volatile consumption became the focus of scientific and engineering research throughout the world. The vast majority of scientific research is based on the further integration of RES and its impact on the stability of the power system [8]. Power system stability is defined as the capability to respond adequately on any operating condition and to fulfil the equilibrium of production and consumption in any disturbing event [9]. In order to successfully address modern power system stability challenges, various management programs for parts of the power system are being introduced. Programs like Demand Response (DR) encompass a whole set of business and management logic on the consumer side. Frequency restoration programs (FRPs) monitor availability and implementation of the reserved capacities required for operating the power system in a stable manner. FRPs are organised into 5 categories: Frequency Containment Reserves (FCR), Imbalance Netting (IN), Automatic frequency restoration reserve (aFRR), manual frequency restoration reserve (mFRR), and optional Replacement Reserve (RR). Many national power systems today use all of these programs and activate them on a daily basis [10], [11].

According to relevant sources, for the Croatian national power grid the amount of energy activated for balancing services ranges from 100 000 MWh to 480 000 MWh annually averaging between 59 MW and 120 MW available power per hour [12]. In comparison with the average consumption of Croatia of 2 GW, this yields to 6

Activation of DR programs, especially tertiary reserve, negatively impacts end-users by impairing their comfort and normal business operations. To adequately solve this problem a hybrid approach is needed with solution outside of the domain.

III. BLOCKCHAIN INFRASTRUCTURE AS POTENTIAL CANDIATE SOLUTION

Blockchain technology as a subset of Distributed Ledger Technologies (DLTs) enables secure transfer of assets without the need for a central authority supported by a distributed digital ledger [1]. The idea behind Blockchain technology was proposed in 2009 by Satoshi Nakamoto with the creation of the first decentralised Peer to Peer (P2P) currency (Bitcoin) [13].

Fundamental concept of Blockchain technology utilises distributed computing power to ensure successful operation of the network and to avoid impersonation by other nodes and taking control of the network (Sybil resistance mechanism). This mechanism is called Proof of Work (PoW) and it is based on investing computational resources and energy into the operation of the network. For their contribution to the stability of the network and their investment of energy the nodes are rewarded by the network with digital assets [14], [15]. This in turn represents a conversion of energy into a digital asset.

Technological concept behind Proof of Work presents an extension to the Hashcash algorithm and is based on the pre-image resistance property of a hash function [16], [17]. The goal is to manipulate the output of a hash function (large integer) so that the numerical conforms to the desired condition ($N_{hashout} < N_{Target}$). As the output of a hash function cannot be correlated with the input (pre-image resistance) to achieve the desired condition the node has to include a random nonce to the input of a hash function alongside with the data that matches the desired condition. By incrementing the nonce and hashing the data+nonce the node will check the fulfilment of the condition and restart the process if the condition is not satisfied. This process is called hashing.

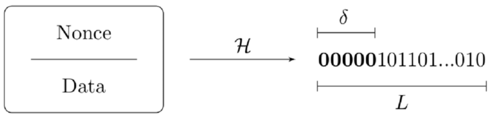

Fig. 1: Hashcash basic structure [17]

Consequently, as every mathematical operation consumes energy, calculation of the hash function output consumes energy that cannot be impersonated by other nodes without the investment of the equivalent energy by themselves. This represents the key concept behind PoW.

Accordingly, the core component of the Proof of Work algorithm is the hash function that needs to be able to calculate the output at a very high frequency. One of the commonly used hash functions in PoW is the SHA256 function from SHA-2 series [18], [19].

With the increase of the number of nodes in the network the output condition of the hash function will change by protocol design, and more attempts will be needed to calculate a valid output of a hash function, in turn increasing total consumption of energy.

A. PoW Blockchain infrastructure hardware

Core of a PoW blockchain hardware functionality is the computation of a hash function (e.g. SHA-256) at a very high frequency. Initial implementation included software implementations on Personal Computers that utilised CPU or GPU for hash calculation. With the increase of nodes in blockchain networks (and computational complexity increase consequently) usage of personal computers for the calculation of hash function became ineffective. This resulted in the birth of Application Specific Integrated Circuits (ASIC) hardware designed for the specific purpose of calculating the output of hash function at a very high throughput and dedicated PoW hardware [20].

ASIC Blockchain infrastructure hardware unit is designed with three main components [21]:

1) *Switch mode power supply* - High power component supplies the rest with DC voltage (often 12V or variable);
2) *Control module* - Often incorporates ARM Cortex based SoC (System on Chip) with Linux based OS and control software;
3) *ASIC Hash boards* - Incorporates individual ASIC for the calculation of hash function output.

Block representation of a BCI hardware unit is shown in Fig. 2

B. Blockchain infrastructure hardware topologies

Blockchain infrastructure is composed of individual hardware units that can be scaled up to large scale installations. Depending on the type of scale up, three most common topologies of BCI exist:

- Distributed small scale solutions (e.g. individual rigs);

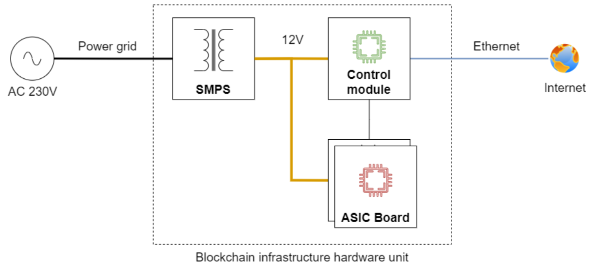

Fig. 2: Blockchain infrastructure hardware unit architecture

- Mobile solutions in intermodal designs (e.g. container solutions);
- Large buildout solutions (e.g. farms).

These topologies vary in maximum power from small scale solutions raining up to 100kW of installed power, to large scale buildout installations ranging from 1MW to 100MW of installed power.

C. Blockchain meets power grid

Contrary to popular belief and practices, PoW Blockchain infrastructure can have a positive impact on the power grid by providing additional stability [22]. The most prospective way to stabilise the power grid is through proven DR programs of activation of control reserves. To take the burden of activation control reserves, especially the tertiary one, from end users, BCI is presented as a solution. This implementation of BCI as a provider of control reserve can only be achieved if BCI would be distributed intelligently and with compliance with technical requirements for activating reservers prescribed by TSOs.

For each type of control, the dynamics of activation and interaction with other types are determined. Slight differences between TSOs exist concerning those activation periods but globally those dynamics are strictly determined by ENTSO-E [23]. Primary control reserve will be activated within 30 seconds and will cover a period of $0 < t < 15min$, secondary control reserve will start its activation immediately after an event and will replace primary control within minutes and be at its maximum within 15 minutes lasting for $0 < t < 60min$. Tertiary control reserve, as it is manually activated one, is the slowest one to respond. Its activation means re-scheduling generation and covers a period of $t > 15min$ and can last for an hour or several hours if there would be more events to compensate. Tertiary control is the one that affects end users the most.

IV. HARDWARE PARAMETER IDENTIFICATION

A. Energy consumption

Energy consumption of a BCI hardware unit can be segmented according to the main components of a unit (Fig 2). In comparison to other components, ASIC boards consume the majority of the energy of an entire unit. Power of a control module, accompanying circuits and

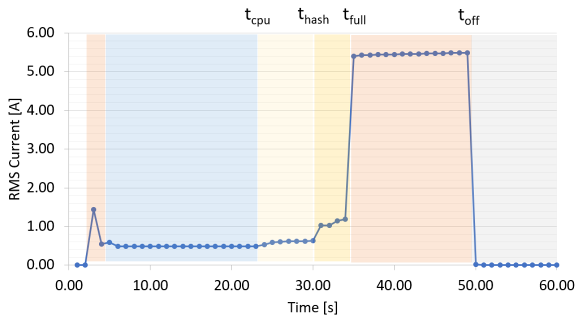

Fig. 3: RMS Current profile of a Antminer S9j

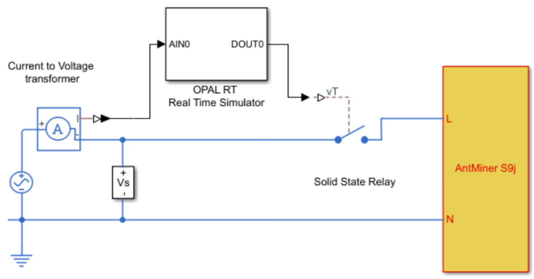

Fig. 4: Measurement testbed

cooling units (fans) account for less than 10% of the total unit power [21].

As the calculation of hash function output depends on blockchain P2P network data the power consumption of a hardware unit is not instantaneous but ramps up gradually. In order to estimate the applicability of BCI hardware for power system balancing, Bitmains Antminer S9j hardware was selected as sample based as one of the most commonly used devices in the past for SHA256 based BCI [2], [24].

Exploratory analysis on power usage of Antminer S9j was conducted in a controlled laboratory environment ($T_{amb} = 25C$) where the RMS Electrical current was analysed in a time domain. Measurement was conducted using digital sample acquisition multimeter (Keysight U1280) with sampling time of $ts = 1s$ for a time period of 60s, where in time $t = 5s$ the device was activated and in $t = 50s$ deactivated. Results are shown in Fig. 3.

From the performed analysis it is possible to identify five key segments of a power profile:

- *Power-up* - Inrush current can be observed in the initial startup period [25]. Assumption for occurrence of inrush current is the charging of SMPS High voltage capacitor where as capacitors charge, current reduces;
- *Operating system boot* - Operating system boot can be observed in periods up to t_{cpu}. Within this interval, power supply is stabilised, but hashing operation is not performed yet;
- *Hash board startup* - In period t_{cpu} to t_{hash} ASIC circuitry is tested and initialisation is performed;
- *Hash board full operation* - From t_{full} current peaks and steady state can be observed. At this point, hash boards become operational and perform hashing operations;
- *Power off* - The segment of powering off the device is not the scope of this work as the powering is performed by Solid State Relay (SSR) that achieves the cutting of power within one half period (10ms).

To validate the power profile of the unit in question parameter identification shall be performed, targeted at time domain analysis and identification of the aforementioned time parameters in the forthcoming section.

B. TESTBED AND PROTOCOL

To ensure proper parameter identification of the power profile time domain a laboratory testbed was set up using OPAL RT Real time simulator's accompanying data acquisition system. Proposed testbed is shown in Fig. 4.

The testbed enables automated measurements and preplanned test scenarios coupled with real-time Hardware-in-Loop technology that enables measurement of multiple iterations of the power profile in question. Parameters for measurement protocol are shown in Table I.

TABLE I: Testbed protocol parameters

No. of runs	100
Run duration [s]	50
Start time [s]	5
Time between runs [s]	20
Sample time [s]	0.0005

C. MODELLING KEY PARAMETERS

Measurement was conducted according to the protocol and testbed described in the previous subsection. Data samples were obtained for every parameter for a total of 100 measurement runs and frequency distribution is plotted in Fig. 5.

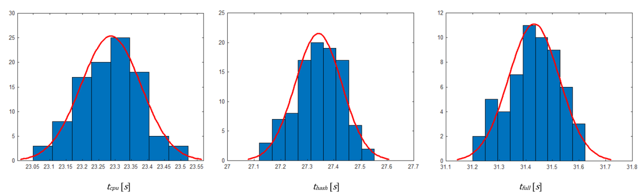
Fig. 5: Frequency distribution for key parameters and Normal distribution fitting

From the calculated frequency distribution the data was fitted to the Normal (Gauss) distribution, depicted by the overlaid red colored plot for each parameter (Fig. 5).

Values of mean and standard deviation were calculated accordingly and the result for each parameter is shown onTable II.

TABLE II: Identification of Normal distribution parameters

Parameter / Fit	μ	σ
t_{cpu} [s]	23.287	0.0919
t_{hash} [s]	27.341	0.0881
t_{full} [s]	31.430	0.0962

D. BLOCKCHAIN INFRASTRUCTURE HARDWARE MODEL

Based on the identified parameters from the previous subsection, a simplified model of a BCI hardware unit is proposed with the identified time parameters as the primary scope of the model, and estimated RMS values of electrical current per segment.

When proposing a simplified model of a Blockchain infrastructure hardware unit, the segments of a power profile defined in the previous section need to be modelled based on the main components defined in Subsection III-A shown in Fig. 6.

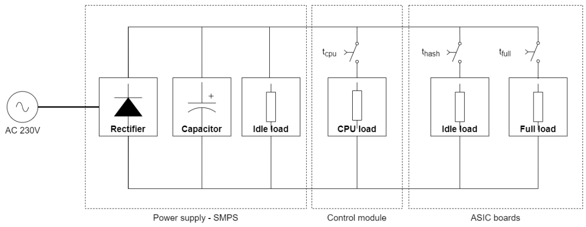

Fig. 6: Simplified model of a BCI hardware unit

As shown in Fig. 6 the proposed model consists of a Power supply module, Control module and ASIC Boards module, all modelled by a time triggered constant DC load. Components were modelled in Matlab Simulink with the Simscape toolbox to match the load values measured. To simulate time parameters normal distribution random number generators were configured with identified parameters from the previous section.

E. Comparison of the model with measurement data

Simulations of the proposed model were performed for the same configuration parameters from Table I with the exception of only one simulation run. The comparison of the measurement and the proposed model is shown in Fig. 7.

From the simulation results, key parameters defined within Section IV were identified and measured to demonstrate the validity of the model: $t_{cpu} = 23.18s$, $t_{hash} = 27.23s$, $t_{full} = 31.21s$. In comparison with the identified and modelled parameters in Section IV-C it can be concluded that simulated parameters fall within 3σ tolerance of the modelled parameters.

V. SCALING MODEL TO BLOCKCHAIN INFRASTRUCTURE SCALE

With the proposed and validated model of a BCI hardware unit, a scale up model can be proposed in order

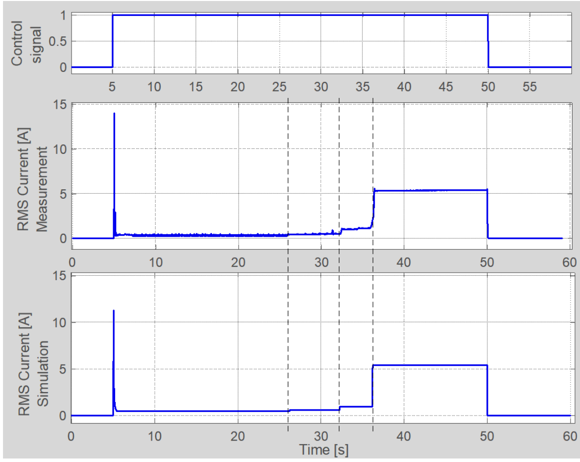

Fig. 7: Simulated model compared to measurement

to validate the time domain behaviour of a large-scale installation and ascertain technical requirements of BCI for power system balancing. Model parameters were defined as:

- 240 hardware units (Antminer S9j model, total power of 300 kW), simulation time 250s (step 0.001 s);
- A simple control mechanism consisting of a 10 step regulator employing Solid State Relays (with 0.1s delay between step activation) for controlling of 24 units (30 kW);
- A control signal was set to mimic the request for reduction and increase of power by the operator (300kW, 150kW, 0kW, 300kW).

Simulation results are shown in Fig. 8. It is observed that the proposed control mechanism in conjunction with BCI achieves a response for increase of power consumption within 35 seconds for 100

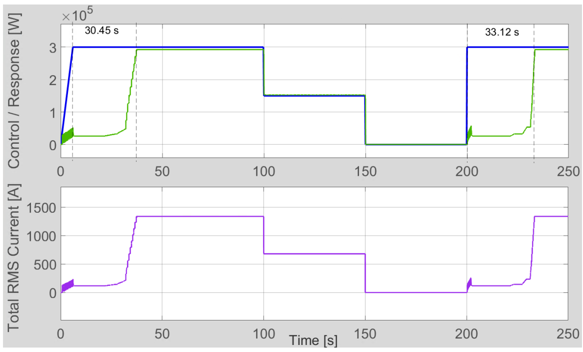

Fig. 8: Scaleup simulated model with control signal

Alternately, when a reduction of power consumption is requested, the proposed solution achieves almost instantaneous response (within 10ms) due to the nature

By comparing the simulation response times between the request and the response of a system to technical requirements of aFRR and mFRR activation times of 30s and 15min respectively a conclusion can be drawn that the modelled BCI hardware can be effectively used for balancing purposes of power systems.

VI. CONCLUSION AND FUTURE WORK

This paper validates key requirements of BCI hardware for power system balancing and provisioning of secondary and tertiary frequency restoration reserve. The approach includes modelling Blockchain Infrastructure (BCI) hardware by means of parameter identification, upscaling and verifying requirements compared to power system standards.

To model the current BCI hardware Bitmains Antminer S9j hardware was selected as sample based as one of the most commonly used devices in the past for SHA256, after which parameter identification on the time domain of a power profile was performed. The model of a hardware unit was proposed and a comparison of simulation and measurement confirmed the validity of the model.

Finally, to verify the applicability of BCI hardware on a large scale installation, a scaleup model with 200 nodes was proposed and simulated for different input power demands. It was concluded that the hardware in question behaves within technical requirements of secondary and tertiary frequency restoration reserve, concluding the applicability of BCI for power system balancing.

Accordingly, it is possible to upgrade existing BCI with a control mechanism that will enable the provisioning of frequency restoration reserve, improving power system stability and adding positive benefits to the stability of a power system as a whole.

Future work will focus on selecting related relevant blockchain hardware, applying the proposed principle of parameter identification, modelling and scaling in order to demonstrate the applicability for providing power system balancing service, also including heterogeneous hardware configurations.

ACKNOWLEDGMENT

This research was co-funded by project “PEGASOS”, through the grant of Croatian Ministry of Regional Development and EU Funds “Increasing the development of the new products and services arising from research and development activities—phase II/KK.01.2.1.02” of the program “Competitiveness and Cohesion 2014–2020” from the European Regional Development Fund.

REFERENCES

[1] S. Aggarwal and N. Kumar, “Chapter seven - basics of blockchain,” in *The Blockchain Technology for Secure and Smart Applications across Industry Verticals*, ser. Advances in Computers, S. Aggarwal, N. Kumar, and P. Raj, Eds. Elsevier, 2021, vol. 121, pp. 129–146.

[2] S. Küfeoğlu and M. Özkuran, “Bitcoin mining: A global review of energy and power demand,” *Energy Research & Social Science*, vol. 58, p. 101273, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214629619305948

[3] T. Ackermann, G. Andersson, and L. Söder, “Distributed generation: A definition,” *Electric Power Systems Research*, vol. 57, no. 3, pp. 195–204, 2001.

[4] P. Du, N. Lu, and H. Zhong, *Demand Response in Smart Grids*. Cham: Springer International Publishing, 2019. [Online]. Available: http://link.springer.com/10.1007/978-3-030-19769-8

[5] M. Bollen and F. Hassan, *Integration of Distributed Generation in the Power System*, L. Hanzo, Ed. IEEE Pres, 2011.

[6] K. Gopalakrishnan, S. K. Khaitan, and S. Kalogirou, *Soft Computing in Green and Renewable Energy Systems*, ser. Studies in Fuzziness and Soft Computing, K. Gopalakrishnan, S. K. Khaitan, and S. Kalogirou, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, vol. 269. [Online]. Available: http://link.springer.com/10.1007/978-3-642-22176-7

[7] A. Zidan and E. F. El-Saadany, “Distribution system reconfiguration for energy loss reduction considering the variability of load and local renewable generation,” *Energy*, vol. 59, pp. 698–707, sep 2013. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2013.06.061https://linkinghub.elsevier.com/retrieve/pii/S0360544213005604

[8] C. Zheng and M. Kezunovic, “Impact of wind generation uncertainty on power system small disturbance voltage stability: A PCM-based approach,” *Electric Power Systems Research*, vol. 84, no. 1, pp. 10–19, mar 2012. [Online]. Available: http://dx.doi.org/10.1016/j.epsr.2011.10.001https://linkinghub.elsevier.com/retrieve/pii/S0378779611002501

[9] M. Gibbard, P. Pourbeik, and D. Vowles, *Front Matter*. University of Adelaide Press, 2015. [Online]. Available: http://www.jstor.org/stable/10.20851/j.ctt1sq5wzz.1

[10] R. Poudineh and T. Jamasb, “Distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement,” *Energy Policy*, vol. 67, pp. 222–231, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.enpol.2013.11.073

[11] M. Merten, C. Olk, I. Schoeneberger, and D. U. Sauer, “Bidding strategy for battery storage systems in the secondary control reserve market,” *Applied Energy*, vol. 268, no. March, p. 114951, 2020. [Online]. Available: https://doi.org/10.1016/j.apenergy.2020.114951

[12] “Izvješće o uravnoteženju za 2018. i 2019. godinu,” *Available online: www.hops.hr , Accessed date: 5 February 2022.*, 2020.

[13] S. Nakamoto, “Bitcoin: A peer-to-peer electronic cash system,” *Decentralized Business Review*, p. 21260, 2008.

[14] Y. Chen, H. Chen, Y. Zhang, M. Han, M. Siddula, and Z. Cai, “A survey on blockchain systems: Attacks, defenses, and privacy preservation,” *High-Confidence Computing*, vol. 2, no. 2, p. 100048, 2022.

[15] Y. Xiao, N. Zhang, J. Li, W. Lou, and Y. T. Hou, *Distributed Consensus Protocols and Algorithms*. John Wiley & Sons, Ltd, 2019, ch. 2, pp. 25–50. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119519621.ch2

[16] A. Back, “Hashcash,” *Published at http://www.cypherspace.org/hashcash/*, 1997.

[17] A. Meneghetti, M. Sala, and D. Taufer, “A survey on pow-based consensus,” *Annals of Emerging Technologies in Computing*, vol. 4, pp. 8–18, 01 2020.

[18] M. S. Ferdous, M. J. M. Chowdhury, and M. A. Hoque, “A survey of consensus algorithms in public blockchain systems for crypto-currencies,” *Journal of Network and Computer Applications*, vol. 182, p. 103035, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1084804521000618

[19] L. Wang, X. Shen, J. Li, J. Shao, and Y. Yang, “Cryptographic primitives in blockchains,” *Journal of Network and Computer Applications*, vol. 127, pp. 43–58, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S108480451830362X

[20] O. Delgado-Mohatar, M. Felis-Rota, and C. Fernández-Herraiz, “The bitcoin mining breakdown: Is mining still profitable?” *Economics Letters*, vol. 184, p. 108492, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0165176519302034

[21] “Antminer s9 repair guide manual,” *Published at https://www.zeusbtc.com/manuals/repair-guide/Antminer-S9-hash-board-Repair-guide.pdf*, 1997.

[22] “Bitcoin is key to an abundant, clean energy future,” *Available online: www.bitcoin.energy , Accessed date: 20 February 2022.*, 2020.

[23] “Ucte operation handbook,” *Available online: www.entsoe.eu , Accessed date: 20 February 2022.*, 2009.

[24] “Digiconomist, bitcoin energy consumption index,” *PAvailable online: https:// digiconomist.net/Bitcoin-energy-consumption , Accessed date: 5 February 2020.*, 2020.

[25] *Transformer Connections*. John Wiley & Sons, Ltd, 2015, ch. 3, pp. 65–100. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119065180.ch3