# DESIGN OF NOVEL CONTROL SCHEMES FOR IMPROVED PERFORMANCE OF AUTOMATIC GENERATION CONTROL

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**by**


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DEPARTMENT OF ELECTRICAL ENGINEERING


Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

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**OCTOBER 2019**

Dedicated to

***My parents & brother***

# Certificate

This is to certify that the dissertation entitled **"Design of Novel Control Schemes for Improved Performance of Automatic Generation Control"** being submitted by **Dushyant Sharma** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is the record of the bonafide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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**Date:** **Dushyant Sharma**

# Abstract

The focus of the thesis is on control of frequency and tie-line power flow in power systems using the well-known concept of automatic generation control (AGC). This thesis aims to develop control schemes that can achieve better frequency regulation and develop schemes which are more suitable for modern power systems which are characterized by few main things. First is the increased penetration of renewable energy sources (RES) e.g., solar photovoltaics (PV) and wind energy conversion systems (WECS). These sources are quite intermittent in nature. Due to fast and random variations in the renewable sources (solar irradiation and wind velocity), these sources can lead to large power oscillations; thereby, giving rise to large and fast frequency variations. Secondly, modern power systems involve increased use of open and distributed channel communications. Such communication channels are needed to support decentralized control services in an electricity market. Such communication schemes introduce a time delay in AGC systems which can even go up to 15 s. Such a large delay in the control loop can make the system unstable and appropriate control scheme needs to be developed for ensuring reliable operation of power system under such conditions. Finally, for remote areas where grid is not available, small scale power systems commonly known as the microgrids are required for electrification. A part of a renewable rich power system may also operate as isolated microgrid in case of grid outage. Thus, microgrid systems having hybrid distributed generations (DGs) (which are mainly RES) are gaining popularity nowadays due to the gradual depletion of fossil fuels, the environmental emission concerns and hike in fuel cost. Such systems consist of distributed energy resources like WECS, PV and energy storing devices like battery energy storage systems (BESS), flywheel energy storage systems (FESS), ultra capacitors (UC), etc. Fast

frequency control in such low inertial systems is quite essential.

In this thesis, controllers have been proposed that gives satisfactory control over the system frequency and tie-line power flow for modern power systems involving increased penetration of RES, increased use of open channel communication and reduced inertia. The controllers developed in this thesis not only lay emphasis on the dynamic performance in terms of settling time, overshoots and undershoots but also on the ease of implementation of the control scheme, reduction in control efforts and reduction in the number of parameters to be tuned. The work starts with developing a non-linear disturbance observer to calculate the change in electrical power in the system and giving a set-point instruction to participating units using feed-forward control instead of traditional feedback control having a proportional integral controller.

Following this, the impact of communication delay caused by the open and distributed channel communication is studied in detail and various new aspects are presented in this thesis. The negative damping introduced in the system is found out with the help of phasor analysis. Various other aspects like the impact of system non-linearities, the impact of controller gains, gains optimization in the presence of communication delay, and modeling of delay for easy analysis are presented in this thesis. Once these aspects are analyzed in detail, a power system frequency stabilizer has been developed to mitigate the stability related issues arising due to the delay caused by the open and distributed channel communication. The developed stabilizer can improve the stability of the system irrespective of the secondary controller used and thus, facilitates the increased use of open channel communication in AGC applications.

Finally, to achieve fast frequency regulation in low-inertia systems, this thesis presents a disturbance observer based control which estimates any change in electrical power (either due to change in load or due to change in power of RES) and gives set-point instruction to participating units accordingly. The feed-forward control approach ensures improved frequency regulation as compared to an integral controller. The design of the observer is also presented in this thesis. The proposed approach is tested in a lab scale microgrid set up in which the frequency of a synchronous generator is controlled using the disturbance observer based approach.

# सार

इस शोध प्रबंध का केंद्र-बिंदु आटोमेटिक जनरेशन कंट्रोल (एजीसी) की प्रसिद्ध अवधारणा का उपयोग करके शक्ति तंत्र में आवृत्ति और टाई-लाइन शक्ति प्रवाह के नियंत्रण पर है। इस शोध प्रबंध का उद्देश्य उन नियंत्रण योजनाओं को विकसित करना है जो बेहतर आवृत्ति विनियमन प्राप्त कर सकें और ऐसी योजनाएँ विकसित कर सकें जो आधुनिक शक्ति तंत्र, जिसकी कुछ मुख्य विशेषतायें हैं, के लिए अधिक उपयुक्त हों। सबसे पहले अक्षय ऊर्जा स्रोतों (आरईएस) की वृद्धि हुई है, जैसे, सौर फोटोवोल्टिक्स (पीवी) और पवन ऊर्जा रूपांतरण प्रणाली (डब्ल्यूईसीएस)। ये स्रोत प्रकृति में काफी अनिरन्तर हैं। नवीकरणीय स्रोतों (सौर विकिरण और वायु वेग) में तेज और यादृच्छिक विविधताओं के कारण, ये स्रोत बड़ी शक्ति दोलनों को जन्म दे सकते हैं; जिसके चलते बड़े और तेज आवृत्ति परिवर्तन में वृद्धि होती है। दूसरे, आधुनिक शक्ति तंत्र में खुले और वितरित संचार माध्यम का उपयोग शामिल है। एक बिजली बाजार में विकेंद्रीकृत नियंत्रण सेवाओं का समर्थन करने के लिए ऐसे संचार माध्यमों की आवश्यकता होती है। इस तरह की संचार योजनाएं एजीसी प्रणालियों में समय की देरी का परिचय देती हैं जो कि १५ सेकंड तक भी जा सकती हैं। नियंत्रण लूप में इतनी बड़ी देरी प्रणाली को अस्थिर कर सकती है और ऐसी स्थितियों के लिए बिजली व्यवस्था के विश्वसनीय संचालन को सुनिश्चित करने के लिए उपयुक्त नियंत्रण योजना विकसित करने की आवश्यकता है। अंत में, दूरदराज के क्षेत्रों के लिए जहाँ ग्रिड उपलब्ध नहीं है, विद्युतीकरण के लिए आमतौर पर माइक्रोग्रिड्स के रूप में ज्ञात छोटे पैमाने की बिजली प्रणालियों की आवश्यकता होती है। अक्षय समृद्ध विद्युत प्रणाली का एक हिस्सा ग्रिड अनुपयोग काल के मामले में पृथक माइक्रोग्रिड के रूप में भी काम कर सकता है। इस प्रकार, हाइब्रिड वितरित उत्पादन (डीजी) (जो मुख्य रूप से आरईएस हैं) वाले माइक्रोग्रिड तंत्र आजकल जीवाश्म ईंधन के क्रमिक गिरावट, पर्यावरणीय उत्सर्जन चिंताओं और ईंधन लागत में वृद्धि के कारण लोकप्रियता प्राप्त कर रहे हैं। इस तरह की प्रणालियों में (डब्ल्यूईसीएस), (पीवी), आदि जैसे वितरित ऊर्जा संसाधन और ऊर्जा भंडारण उपकरण जैसे बैटरी ऊर्जा भंडारण प्रणाली (बिईएसएस),

चक्का ऊर्जा भंडारण प्रणाली (एफ़ईएसएस), अल्ट्रा कैपेसिटर (युसी), आदि शामिल होते हैं। इस तरह की कम जड़त्वीय प्रणालियों में तेज आवृत्ति नियंत्रण काफी आवश्यक है।

इस शोध प्रबंध में, नियंत्रकों का प्रस्ताव किया गया है जो आरईएस के बढ़ते प्रवेश, खुले संचार माध्यम के उपयोग में वृद्धि और कम जड़ता वाले आधुनिक शक्ति तंत्र के लिए तंत्र आवृत्ति और टाई-लाइन शक्ति प्रवाह पर संतोषजनक नियंत्रण देता है। इस शोध प्रबंध में विकसित नियंत्रकों ने न केवल निपटान समय, उतार-चढ़ाव के मामले में गतिशील प्रदर्शन पर जोर दिया, बल्कि नियंत्रण योजना के कार्यान्वयन में आसानी, नियंत्रण के प्रयासों में कमी और मिलान किए जाने वाले मापदंडों की संख्या में कमी पर भी जोर दिया। कार्य प्रणाली में विद्युत शक्ति में परिवर्तन की गणना करने के लिए एक गैर-रेखीय अशांति पर्यवेक्षक के विकास के साथ शुरू होता है और आनुपातिक एकीकरण वाले पारंपरिक प्रतिक्रिया नियंत्रण के बजाय फ़ीड-फ़ॉरवर्ड नियंत्रण का उपयोग करके भाग लेने वाली इकाइयों को एक सेट-पॉइंट निर्देश देता है।

इसके बाद, खुले और वितरित संचार माध्यम के कारण संचार में देरी के प्रभाव का विस्तार से अध्ययन किया गया है और इस शोध प्रबंध में विभिन्न नए पहलुओं को प्रस्तुत किया गया है। तंत्र में शुरू की गई नकारात्मक अवमंदन का फेज़र विश्लेषण की मदद से पता चला है। तंत्र में गैर-रैखिकता के प्रभाव, नियंत्रक गुणक के प्रभाव, संचार देरी की उपस्थिति में गुणक अनुकूलन और आसान विश्लेषण के लिए देरी के प्रतिरूपण जैसे विभिन्न अन्य पहलुओं को शोध प्रबंध में प्रस्तुत किया गया है। एक बार इन पहलुओं का विस्तार से विश्लेषण करने के बाद, खुले और वितरित संचार माध्यम की वजह से देरी के कारण उत्पन्न होने वाली स्थिरता के मुद्दों को कम करने के लिए एक शक्ति तंत्र आवृत्ति स्थायीकारक विकसित किया गया है। विकसित स्थायीकारक उपयोग किए जाने वाले माध्यमिक नियंत्रक के निरपेक्ष प्रणाली की स्थिरता में सुधार कर सकता है और इस तरह एजीसी अनुप्रयोगों में खुले संचार माध्यम के उपयोग में वृद्धि की सुविधा देता है।

अंत में, कम-जड़ता प्रणालियों में तेजी से आवृत्ति विनियमन को प्राप्त करने के लिए, यह शोध प्रबंध एक अशांति पर्यवेक्षक आधारित नियंत्रण प्रस्तुत करता है जो विद्युत शक्ति में किसी भी बदलाव का अनुमान लगाता है (या तो खेप में परिवर्तन के कारण या आरईएस की शक्ति में परिवर्तन के कारण) और तदनुसार इकाइयों में भाग लेने के लिए सेट-पॉइंट निर्देश देता है। फ़ीड-फ़ॉरवर्ड नियंत्रण दृष्टिकोण एक एकीकरण नियंत्रक की तुलना में बेहतर आवृत्ति विनियमन सुनिश्चित करता है। प्रेक्षक की रचना को भी इस शोध प्रबंध में प्रस्तुत किया गया है। प्रस्तावित दृष्टिकोण का परीक्षण एक प्रयोगशाला स्तर माइक्रोग्रिड में किया है जिसमें एक सिंक्रोनस उत्पादन-यन्त्र की आवृत्ति को अशांति पर्यवेक्षक आधारित दृष्टिकोण का उपयोग करके नियंत्रित किया है।

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# Abbreviations

| | |
|---|---|
| AGC | Automatic generation control |
| ALFC | Automatic load frequency control |
| GRC | Generation rate constraints |
| PV | Photovoltaic |
| WECS | Wind energy conversion system |
| FC | Fuel cell |
| RES | Renewable energy sources |
| PI | Proportional integral |
| PID | Proportional integral derivative |
| ID | Integral derivative |
| IDD | Integral double derivative |
| ACE | Area control error |
| DG | Distributed generation |
| DER | Distributed energy resources |
| BESS | Battery energy storage system |
| FESS | Flywheel energy storage system |
| UC | Ultra capacitor |
| DEG | Diesel engine generator |
| DOBC | Disturbance observer based control |
| PSO | Particle swarm optimization |
| TLBO | Teaching learning based optimization |
| LMI | Linear matrix inequalities |

| | |
|---|---|
| PLFC | Predictive load frequency control |
| NPLFC | Non-predictive load frequency control |
| AE | Aqua electrolyzer |
| NDO | Non-linear disturbance observer |
| PSS | Power system stabilizer |
| PSFS | Power system frequency stabilizer |
| ISE | Integral squared error |
| ITSE | Integral time squared error |
| IAE | Integral absolute error |
| ITAE | Integral time absolute error |
| SLP | Step load perturbation |
| WSCC | Western System Coordinating Council |
| DSO | Digital storage oscilloscope |
| WTG | Wind turbine generator |
| VSC | Voltage source converter |
| MPPT | Maximum power point tracking |
| PMU | Phasor measurement unit |
| UFLS | Under frequency load shedding |