GSC 2021—The Annual Workshop of Graduate Students in Systems & Control

Under the auspice of IAAC – the Israeli Association for Automatic Control

Monday, May 3, 2021

Faculty of Civil and Environmental Engineering, Technion

Zoom Meeting ID: 935 1722 4286

Dear Friends and Colleagues,

As previously announced the **Annual Workshop of Graduate Students in Systems & Control GSC 2021** will take place on **Monday May 3rd**, 2021. Due to Covid-19 restrictions this year workshop will be **hybrid**. The in-person event will take place at the Grand Water Research Institute auditorium (Faculty of Civil and Environmental Engineering) at Technion. In-person participation will be restricted to 60 people with appropriate proof of vaccination/recovery. On-line participation via Zoom is opened to all (presenters and audience).

Please register at the following link:

https://forms.office.com/Pages/ResponsePage.aspx?id=TCxQ8S7uHEGXFchV9nU7hLnq-tj87G1DqlLOOdeaL55UNjYyMjJZMzJGMExNUzhUOUlLV1Q3VUxXNi4u

Registration is mandatory for in-person participation. Registration for in-person participation will be closed on Friday May 30.

In-person attendance will be granted based on a "first registered-first served" basis. Please keep in mind that by signing up you may be preventing someone else from attending so don't sign-up if you are not sure you will attend in person.

Looking forward to seeing you all at the meeting

Rafi Linker (GSC 2021 organizer)

Moshe Idan (IAAC President)

GSC 2021 - The Annual Workshop of Graduate Students in Systems & Control
Monday May 3, 2021
Auditorium of the Grand Water Research Institute
Faculty of Civil and Environmental Engineering, Technion
Zoom Meeting ID: 935 1722 4286
PROGRAM

08:50 Opening remarks
09:00 Optimal Gliding Trajectories with Altitude-Dependent Wind
Meir Halachmi, EE, Technion, M.Sc. Supervisor: Nahum Shimkin
09:20 An Improved Distributed Consensus Kalman Filter Design Approach
Aviv Priel, AE, Technion, M.Sc. Supervisor: Daniel Zelazo
09:40 Learning Contact-Rich Skills Using Residual Admittance Policy
Oren Spector, ME, Technion, M.Sc. Supervisor: Miriam Zacksenhouse
10:00 Break
10:10 Minimum Combined Time-Energy Optimal Control of a Non-Linear Surface Vehicle Subject to Disturbances
Ayal Taitler, TASP, Technion, Ph.D. Supervisors: Erez Karpas, Per-Olof Gutman
10:30 On Sampled-Data Consensus: Divide and Concur
Gal Barkai, ME, Technion, Ph.D. Supervisors: Leonid Mirkin, Daniel Zelazo
10:50 Online Adaptive Step Size Selection for Tracking and Navigation Kalman Filters
Barak Or, Marine Technologies, Haifa U., Ph.D. Supervisor: Itzik Klein
11:10 Compound Matrices in Systems and Control Theory
Eyal Bar-Shalom, EE, TAU, Ph.D. Supervisor: Michael Margaliot
11:30 k-contraction in a Serial Interconnection of Systems
Ron Ofir, EE, Technion, Ph.D. Supervisors: Yoash Levron, Michael Margaliot
11:50 Minimum-Effort Guidance Using Second-Order Approximate Kinematics
Gleb Merkulov, AE, Technion, Ph.D. Supervisors: Tal Shima, Martin Weiss
12:10 break
12:20 Plenary Talk: Feedback traffic control for future urban air mobility
Assoc. Prof. **Jack Haddad**, Faculty of Civil and Environmental Engineering, Technion
13:10 Lunch break
14:00 Finite-Dimensional Observer-Based Control of Parabolic PDEs with Unbounded Measurement and Control Operators.
Rami Katz, EE, TAU, Ph.D. Supervisor: Emilia Fridman
14:20 H_2 Performance in Networked Control: Effects of Sampling Rate Variability
Maor Braksmayer, ME, Technion, Ph.D. Supervisor: Leonid Mirkin
14:40 Saturating PI Control of Stable Nonlinear Systems Using Singular Perturbations
Pietro Lorenzetti, EE, TAU, Ph. D. Supervisor: George Weiss
15:00 Abstract Nonlinear Control Systems
Shantanu Singh, EE, TAU, Ph.D. Supervisor: George Weiss
15:20 Time Optimal Dubins Path Via an Intermediate Circle
Bhargav Jha, AE, Technion, Ph.D. Supervisor: Tal Shima
15:40 Stabilizing a Network of Virtual Synchronous Machines with Virtual Friction
Florian Reissner, EE, TAU, Ph.D. Supervisor: George Weiss
End

Plenary Talk

Feedback Traffic Control for Future Urban Air Mobility

Assoc. Prof. Jack Haddad

Faculty of Civil and Environmental Engineering, Technion

The imminent penetration of low-altitude passenger and delivery aircraft into the urban airspace will give rise to new urban air transport systems, which we call low-altitude air city transport (LAAT) systems. As the urban mobility revolution approaches, we must investigate (i) the collective behaviour of LAAT aircraft in cities, and (ii) ways of controlling LAAT systems. Similar to road transport systems, increasing numbers of passenger and delivery aircraft will cause urban air traffic congestion, and raise new air traffic control challenges. Given operational differences between conventional airplane and LAAT systems, future aircraft cannot be managed by the current or adapted aircraft management schemes. Future LAAT systems exemplify a new class of modern large scale engineering systems - networked control systems. They are spatially distributed, consist of many interconnected elements with control loops through digital communication networks such that the systems' signals can be exchanged among all components through a common network. From a feedback control design perspective, the aircraft flow control problem will integrate the controlled system, which is described by equations in continuous time while the controller is implemented in discrete time. Inspired by controlled urban road networks, the goal is to develop a new operational concept: flows of aircraft traffic, rather than individual aircraft, should be controlled. We will translate the well-established idea of flow control from road traffic systems to LAAT systems by addressing the modeling and control challenges resulting from the fundamental flow-oriented differences between ground traffic and low-altitude air traffic. A network aggregate approach of modeling and control would address all potential issues of LAAT systems, if we revisit modeling and control development to integrate the 3rd dimension of airspace.

Optimal Gliding Trajectories with Altitude-Dependent Wind

Student name: Meir Halachmi

Affiliation: Faculty of Electrical Engineering, Technion

Studying towards: M.Sc.

Thesis supervisor: Nahum Shimkin

Optimal gliding is a well-researched problem, with different variants and approaches. One variant of interest is the altitude-loss minimization problem, when gliding between two given points. The difficulty of solving this problem heavily depends on the set of assumptions on the aircraft model and environment conditions. In this paper, we focus on finding the optimal trajectory under altitude-dependent wind profiles. Our main theoretical finding is that the optimal trajectory must maintain throughout a constant flight direction with respect to the current wind direction. In addition, we show that although the optimal gliding airspeed changes with altitude, it can be calculated locally at each altitude. In the final part of the analysis, we compare the optimal trajectory to an alternative solution -- the best possible straight-line trajectory, in order to demonstrate the benefit of the optimal solution, compared to the simpler straight-line solution.

An Improved Distributed Consensus Kalman Filter Design Approach

Student name: Aviv Priel

Affiliation: Faculty of Aerospace Engineering, Technion.

Studying towards: M.Sc.

Thesis supervisor: Daniel Zelazo

Sensor networks comprise a group of agents equipped with sensing devices and communicating capabilities in order to solve the common task of cooperative sensing and estimation of a detectable physical process. In this framework, each agent in the system activates, in a distributed fashion, an estimator which relies on local measurements of the process fused with the estimates from other

agents in the network. A recently developed tool to solve this problem is the introduction of a consensus-based term fused with a classical state estimator structure. Specifically our focus in this research shall be on the distributed Kalman Consensus filter, activated by each agent. In this architecture, each agent estimator incorporates a classic Kalman filter term, along with a consensus term used to fuse the estimates from neighboring agents in a diffusive manner. The main analytical challenge in this estimator structure is the design of the consensus gain term that ensures the stability of the estimator while maintaining a prescribed degree of performance.

In this work we consider both centralized and decentralized approaches to the design and implementation of these Kalman consensus filters. In the centralized case, we begin with results from the seminar work of Olfati-Saber and propose a method based on semi-definite programming to compute the consensus gain term leading to improved performance of the estimator. In the decentralized case, we introduce a consensus gain that can be computed by each agent and relies only on local network properties, i.e., the number of neighbors each agent can communicate with. In this regard, our scheme can handle time-varying communication networks while ensuring stability of the estimator error dynamics. Our design approaches were validated for different scenarios utilizing multiple numerical simulations. A performance comparison between our proposed filters, filters existing in the literature, and the classic Kalman filter (non-cooperative case) was conducted. Our proposed filter demonstrated superiority in performance and robustness for a variety of network properties and noise characteristics.

Learning Contact-Rich Skills using Residual Admittance Policy

Student name: Oren Spector

Affiliation: Faculty of Mechanical Engineering, Technion

Studying towards: M.Sc.

Thesis supervisor: Miriam Zacksenhouse

Reinforcement learning (RL) offers a promising framework to learn control policies that can generalize well. However, pure RL might impractical for real-life contact-rich tasks due to sample inefficiency. Therefore, there is a growing interest in exploiting prior knowledge about the task, using residual learning or learning from demonstration. Nevertheless, learning general policies still requires extensive trials on the real-robot, which may be expensive and hazardous. To address those issues, we propose to learn a residual admittance policy (RAP) in simulations, and demonstrate that it can be transferred directly to the real robot. RAP is learned using RL to correct the movements generated by a baseline policy in the framework of dynamic movement primitives. Given the reference trajectories generated by the baseline policy, the action space of RAP is limited to the admittance parameters only. This is a key element in facilitating direct transfer of the policy learned in simulations to the real robot. We demonstrated that

RAP can generalize well over space, size and shape, and facilitates quick transfer learning. Most impressively, we demonstrated that the policy learned in simulations is highly successful in controlling a real robot (UR5e) to insert pegs of different shapes and sizes, without further training.

Minimum Combined Time-Energy Optimal Control of a Non-Linear Surface Vehicle Subject to Disturbances

Student name: Ayal Taitler

Affiliation: Technion Autonomous Systems Program.

Studying towards: Ph.D.

Thesis supervisors: Erez Karpas and Per-Olof Gutman

The problem of a planar vehicle moving on a surface, such as aerial drones or small naval vessel can be treated as series of trajectory planning problems between way-points. While nominally the movement between each two fourth dimentional points (positions and velocities) can be treated as a 1D projection of the movement on the vector connecting the two points, in the presence of arbitrary disturbance the full problem on a plane must be considered. The combined minimum-time-energy optimal solution is now dependent on the value and direction of the disturbance, which naturally affects the structure and completion of the movement task. In this work, we address the minimum time-energy problem of a movement on a 2D plane with quadratic drag, under norm state (velocity), and norm control (acceleration) constraints. The structure and properties of the optimal solution are found and analyzed. The Pontryagin Maximum Principle (PMP) with control and state constraints is utilized. Simulations supporting the results are provided and compared with those of the open-source academic optimal control solver Falcon.m.

On Sampled-Data Consensus: Divide and Concur

Student name: Gal Barkai

Affiliation: Faculty of Mechanical Engineering, Technion

Studying towards: Ph.D.

Thesis supervisors: Leonid Mirkin and Daniel Zelazo

Reaching an agreement, or consensus, between autonomous integrator agents is a fundamental problem in multi-agent systems. It serves as a blueprint for more complex cooperative tasks, and admits an elegant solution derived from graph theory in both continuous- and discrete-time settings. This work studies sampled-data implementation of the protocol under intermittent and asynchronous information exchange. Treating such a problem via discretizing the agents under the conventional zero-order-hold (ZOH) introduces considerable complexity. Intermittent sampling adds uncertainty to the gain, while asynchronization adds parametric uncertainty. Existing protocols counter these uncertainties through the use of very conservative gains.

We depart from the conventional ZOH-based paradigm and propose a structure in which control signals are generated by analog emulators of an ``ideal'' world. Each agent emulates the entire ensemble as if all are running an analog consensus protocol, and opportunistically broadcast its sampled, emulated centroids to neighbours. Once an agent receives such a broadcast, it updates the local emulator with the new data. This particular emulation and update scheme facilitates a separation between emulator's disagreements and centroids, which substantially simplifies the analysis. Convergence is guaranteed under very mild assumptions. Moreover, the implementation complexity of the controller can be rendered invariant to the number of agents in the system.

Online Adaptive Step Size Selection for Tracking and Navigation Kalman Filters

Student name: Barak Or

Affiliation: Department of Marine Technologies, University of Haifa

Studying towards: Ph.D.

Thesis supervisor: Itzik Klein

In Kalman filtering, a trade-off exists when selecting the filter step size. Generally, a smaller step size improves the estimation accuracy, yet with the cost of a high computational load.

In this research, two approaches for an appropriate choice of an adaptive step size are presented. The first approach is based on a novel criterion for tracking applications under the assumption that all measurements arrive simultaneously, and the second approach is based on a supervised machine learning online tuning scheme for aided inertial navigation systems (INS) sensor fusion.

In the first approach, a criterion that acts as a guideline for a reasonable choice of the step size is suggested. It is based on the predictor-corrector error covariance matrices of the discrete Kalman filter. In addition, this criterion is elaborated to an adaptive algorithm, for the case of a time-varying measurement noise covariance.

The second approach addresses aided INS scenarios. There, the step size parameter is responsible for the solution frequency update, and eventually, its accuracy. Generally, the aiding sensors update frequency is considered much slower compared to the INS operating frequency (hundreds Hertz). Such high rate is unnecessary for most platforms, specifically for low dynamics vehicles. A supervised machine learning-based online tuning scheme to select the proper INS step size in real time is proposed. To that end, a velocity error bound is defined, allowing the aided INS to act in a sub-optimal working conditions, and yet minimize the computational load.

For both approaches simulation examples, and field experiments using a quadcopter are presented and analyzed to show the benefits of the proposed approaches.

Compound Matrices in Systems and Control Theory

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Studying towards: Ph.D.

Thesis supervisor: Michael Margaliot

The multiplicative and additive compounds of a matrix play an important role in several fields of mathematics including geometry, multi-linear algebra, combinatorics, and the analysis of nonlinear time-varying dynamical systems. There is a growing interest in applications of these compounds, and their generalizations, in systems and control theory.

We provide a gentle introduction to these topics with an emphasis on the geometric interpretation of the compounds, and describe some of their recent applications.

k-contraction in a Serial Interconnection of Systems

Student name: Ron Ofir

Affiliation: Faculty of Electrical Engineering, Technion

Studying towards: Ph.D.

Thesis supervisors: Yoash Levron and Michael Margaliot

Contraction theory plays an important role in systems and control, with applications in robotics, systems biology, neuro-science, and more. The flow of contracting systems contracts lines (that is, 1-dimensional polygons) at an exponential rate. This implies a highly ordered asymptotic behavior: in a time-invariant contracting system all trajectories converge to a globally asymptotically stable equilibrium point, whereas in a time-varying and T-periodic contracting system all trajectories converge to a globally asymptotically stable limit cycle with period T. However, these strong results limit the use of contraction theory to systems with no more than a single equilibrium point. In this light, several generalizations exist, each fitting a wider class of systems while giving somewhat weaker convergence results.

A recent generalization is called k-contracting systems. These contract the volume of k-dimensional polygons at an exponential rate. For k=1, these reduce to standard contracting systems. The case of k=2 was studied by Muldowney and Li, who showed that in the autonomous case, every bounded trajectory converges to an equilibrium point. In contrast to standard contracting systems, the equilibrium point is not necessarily unique, making 2-contraction possibly applicable to systems with multiple or even an infinite number of equilibrium points.

An important property of contraction theory is that the interconnection of several contracting sub-systems generates a contracting system. In this talk, we present novel results on the serial interconnection of 1-contracting and 2-contracting systems. We provide sufficient conditions guaranteeing that such systems have a "well-ordered" asymptotic behavior, proving that no periodic solutions exist, or under stronger conditions, that all bounded trajectories converge to an equilibrium point. We demonstrate our results on a simple power system consisting of two interconnected synchronous generators.

Minimum-Effort Guidance Using Second-Order Approximate Kinematics

Student name: Gleb Merkulov

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Studying towards: Ph.D.

Thesis supervisor: Tal Shima and Martin Weiss

A guidance law for intercepting a stationary target is derived based on solving the minimum effort optimal control problem with fixed time and a second order approximation of the kinematic equations. It is proven that this optimal control problem has, in general, a unique solution. Based on this solution, a guidance law is proposed that is shown to be implementable based on typically available sensor data, using a semi-analytic procedure. Numerical simulations show that the solution based on the second-order approximate kinematics matches closely the solution based on nonlinear kinematics that can only be obtained by numerical optimization.

Finite-Dimensional Observer-Based Control of Parabolic PDEs with Unbounded Measurement and Control Operators

Student name: Rami Katz

Affiliation: School of Electrical Engineering, Tel-Aviv University

Studying towards: Ph.D.

Thesis supervisor: Emilia Fridman

Finite-dimensional observer-based controller design for PDEs is a challenging problem. In my talk on GSC'20, a constructive LMI-based method for design of such controllers via modal decomposition approach was introduced for the 1D heat equation, under the assumption that one of the control and observation operators is bounded. In this talk, such controllers will be presented for the 1D linear heat and Kuramoto-Sivashinsky equations, where both operators are unbounded. We employ a modal decomposition approach via dynamic extension, using eigenvalues and eigenfunctions of a Sturm-Liouville operator. The controller dimension is defined by the number of unstable modes N_0, whereas the observer dimension N may be larger than N_0. We suggest a direct Lyapunov approach to the closed-loop system, which results in LMIs, whose elements and dimension depend on N. The value of N and the decay rate are obtained from the LMI. We prove that the LMIs are always feasible for large enough N. We then describe how the Lyapunov analysis can be improved by deriving reduced-order LMIs, whose dimension is independent of N. Finally, sampled-data implementation of our observer-based control under quantization will be presented.

H_2 performance in networked control: effects of sampling rate variability

Student name: Maor Braksmayer

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Studying towards: Ph.D.

Thesis supervisor: Leonid Mirkin

In classical sampled-data systems, where sampling is assumed to be periodic, it is well known that the closed-loop performance is monotonically improving with the increase of the sampling rate. Yet, the periodic sampling assumption cannot be made in networked control applications. This gives rise to networked control problems with intermittent feedback and varying sampling rate. An intriguing observation made in the H2 optimization under intermittent communication, although for a simple numerical example only, is that the optimal performance level depends not only on the average sampling rate, but also on its variability. This naturally raises the question about the effects of the variability of the sampling rate on the attainable optimal cost in networked control applications. In this talk I will try and answer this question. I will present tight upper and lower bounds on the attainable optimal cost derived for fixed maximal and average sampling intervals. These bounds are simple and insightful, for they show that the best /worst performance is attained under sampling instances with the lowest / highest variances under a fixed mean. Therefore, a slower yet more consistent sampling may be advantageous. Further insight into the dependence of the performance on properties of the sampling sequence will be provided in several special cases.

Saturating PI Control of Stable Nonlinear Systems Using Singular Perturbations

Student name: Pietro Lorenzetti

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Studying towards: Ph.D.

Thesis supervisor: George Weiss

Proportional-Integral (PI) control is extensively used to achieve robust asymptotic tracking and disturbance rejection of constant external signals (it is the simplest instance of the internal model principle). When the plant is an uncertain linear system, closed-loop stability can be achieved if the control gains are sufficiently small and the plant fulfils certain stability conditions [4]. The theory has been extended to nonlinear systems in [1], using singular perturbation tools.

In the presence of actuator limitations, e.g. saturation, there can be a mismatch between the actual plant input and the controller output. When this happens, the controller output does not drive the plant and the states of the controller are wrongly updated. If the controller is unstable (such as PI), then its state may reach a region far from the normal operating range, an effect called controller windup [2]. Windup may cause long transients, oscillations and even instability.

This talk presents an anti-windup PI design for stable nonlinear systems. This PI controller uses a saturating integrator, which ensures that the integrator state is constrained to a compact interval chosen based on physical constraints. The saturating integrator is straightforward to implement and it has proven to be effective in power electronics applications. Our main result, based on singular perturbation theory, shows that, under assumptions similar to [1], for small enough controller gain, the closed-loop system is (locally) exponentially stable and the region of attraction of its equilibrium point contains a curve of equilibrium points of the open-loop system. The talk is mainly based on [3]. (We will also mention some applications and extensions.)

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[2] M. V. Kothare, P. J. Campo, M. Morari, and C. N. Nett, “A unified framework for the study of anti-windup designs”, Automatica, vol. 30, 1994, pp. 1869-1883.

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[4] M. Morari, “Robust stability of systems with integral control”, IEEE Trans. on Automatic Control, vol. 30, 1985, pp. 574-577.

Abstract Nonlinear Control Systems

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Studying towards: Ph.D.

Thesis supervisor: George Weiss

Introduction. We describe a class of abstract nonlinear infinite dimensional systems, whose state space is a Hilbert space X, by a differential inclusion of the form:

$$\dot{x}(t) \in Ax(t) - \Lambda\big(x(t)\big) + Bu(t) \tag{1}$$

Here $x(t) \in X$ is the state of the system and $u(t) \in U$ is the input. The operator A is the generator of a strongly continuous semigroup of linear operators on X and Λ is a maximal monotone (possibly set-valued) operator with $D(\Lambda) = X$ (i.e. Λ is similar to a bounded linear operator).

We focus our attention to systems for which, the operators A and B have a special structure. Such structures are encountered in a class of systems often called the Maxwell class of systems. The linear version of this class of systems are often encountered in mathematical models of vibrating systems with damping. The special structure of this class of systems is prominent when we look at Maxwell's equations on a bounded domain, which model the electromagnetic field in a domain, with electromagnetic waves coming in from outside the domain, as inputs. In the nonlinear version that we consider, the current density may be a nonlinear monotone function of the electric field intensity as is the case when the domain contains a special material (for instance a semiconductor).

Motivation. Apart from the Maxwell's equations in a bounded domain containing some special material, we often encounter such nonlinear infinite dimensional systems in physics. For instance, while modeling a wind turbine tower with nacelle (based on NASA Space Control Laboratory Experiment model, popularly referred to as SCOLE model) coupled with a tuned mass damper (TMD) used to suppress the vibrations in the tower (a beam). The nonlinear damping term appears as static friction between the surface of the nacelle and the TMD. In our work we investigate the well-posedness of the nonlinear system described by the differential inclusions (1).

Main result. We show that under suitable assumptions, the nonlinear system represented by (1) is well-posed, moreover its solution is right differentiable and Lipschitz continuous on any finite time interval. Our approach uses the theory of maximal monotone operators and the Crandall-Pazy theorem about nonlinear contraction semigroups, which we apply to the Lax-Phillips type nonlinear semigroup that represents the entire system, i.e. the state and the input function. We also use the perturbation theorem of maximal monotone operators from Rockafellar to prove that the Lax-Phillips type nonlinear semigroup representing system (1) is contractive. Our generalized results are applied to the nonlinear version of the Maxwell's equations and the famous SCOLE model coupled with a TMD in presence of a nonlinear damping term (representing static friction).

Time optimal Dubins Path Via an Intermediate Circle

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Studying towards: Ph.D.

Thesis supervisor: Tal Shima

Our work characterizes the time optimal Dubins path between a given pair of configurations (a location and a heading orientation), via the boundary of an intermediate circle. The intermediate circle can be static or moving on a parametric curve. Such paths are fundamentally required in surveillance and collision avoidance problems. Catering to this requirement, we will present some geometrical properties of the time optimal Dubins path obtained by using Pontriyagin's maximum principle and analyzing the necessary conditions for state inequality constraints. These geometrical properties will allow us to narrow down the candidate optimal paths to a finite set. Further, we will present an intuitive way to devise a semi-analytical solution of each type of candidate paths using the aforementioned properties. Finally, the talk will conclude with an analysis of computational costs and numerical examples highlighting the importance of the work and future directions.

Stabilizing a network of virtual synchronous machines with virtual friction

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With the rise of renewable energy sources, power grids all over the world see an increasing percentage of energy supplied by inverters as opposed to synchronous machines. This technological shift raises new issues as many stability promoting features, inherent in synchronous generators, are absent in inverters. The requirement to improve grid stability and robustness can be addressed by virtual synchronous machines (VSMs), as a special type of switched power converters. These are controlled such that they mimic (towards the power grid) the behaviour of synchronous generators, providing frequency and voltage droop as well as (virtual) inertia. Their main advantage, as compared to current source inverters common in renewable energy sources, is that they can form stable grids, just like synchronous generators (SGs).

A major issue with VSMs employing frequency droop control is that they have to inject large excess power during disturbances where the grid frequency drops below its nominal value. Hardware power ratings of the electronic components and/or the limited availability of excess DC power impose an upper bound for the frequency droop constant and/or they force the droop torque to saturate, which is bad for stability. To avoid reaching saturation frequently, the frequency droop constant (per unit) employed in inverters is typically much smaller than that imposed on the prime mover of an SG, thus limiting their capability to provide frequency support to the grid.

In order to decouple stability requirements from hardware requirements, we propose to introduce **virtual friction (VF)**, as an additional viscous friction torque, acting on the virtual rotors of the connected VSMs. This torque employs the center of inertia frequency of the grid as a reference instead of the nominal frequency. We can prove that VF is highly effective in stabilizing inter area oscillations.

In order to analyze the impact of virtual friction, we follow two approaches:

- A theoretical proof of stability based on the network reduced power system (NRPS) model, a simplified model that consists essentially in a coupled system of order 2 swing equations. We extend this model by VF terms and prove that their addition enhances the model stability (the formal proof of this is not shown here)
- Simulations employing a full VSM algorithm and a more realistic representation of the electrical grid.

In our simulations, we employ a two area network (see Fig. 1) with a disturbance occurring in one of the two areas at some instant in time. This disturbance causes an oscillating exchange of power between the two areas which reveals itself in the VSM power output, virtual frequency and the (virtual) relative rotor angles two VSM have with respect to each other.

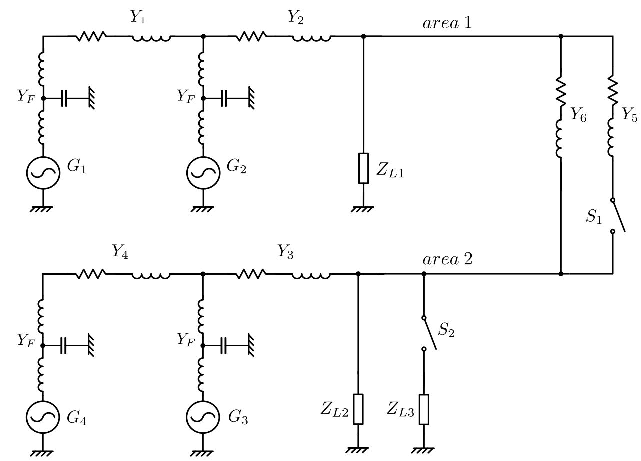

Fig. 1. Simulated two area grid with four generators (3 phase grid). Switch S_1 is used to change the line impedance between the two areas and S_2 is used to connect load L_3.

Fig. 2 shows a simulation result for the four generators after a sudden disconnection of load L_3, leading to a step change of the active power consumption in area 2 at $t = 30$s. Poorly damped oscillations between the two areas with a frequency of 0.64Hz are induced when VF is not active (see Fig. 2a). If VF is used, oscillations are fully suppressed (see Fig. 2b)

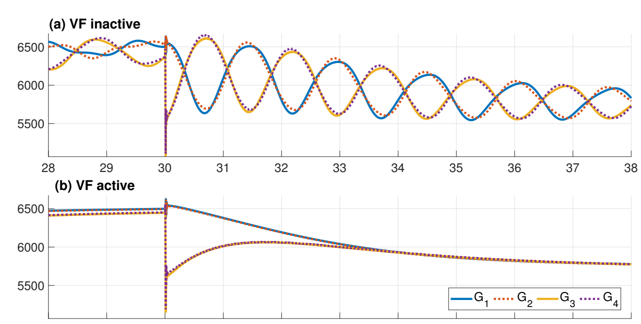

Fig. 2. The plots of active power output (in W) following the disconnection of load L_3 starting at $t = 30$s. Subfigure (a) shows the plots without VF, while subfigure (b) shows the much smoother transition with VF.