A Short History of Hydropower Control

by Karl Heinz Fasol

Today's control systems have their roots, to a great extent, in the speed control of driving engines (prime movers) and particularly in the speed control of water turbines. The first turbines with automatic speed control appeared sometime in the mid-19th century. In this column, I discuss the history of water-turbine control systems, noting the older inventions and techniques that made possible the very first attempts to control the speed of hydraulic machinery and recognizing the key engineers and scientists who contributed to the further development.

Waterwheels and Early Turbines

Hydropower was used in China at least 2000 years ago; the waterwheel was invented in ancient Greece and Rome, and in the year 13 B.C., the Roman engineer and writer Marcus Vitruvius Pollio described a grain mill driven by a waterwheel and a cogwheel gear. Archeologists later proved the early existence of such drives of mills and of waterwheels used for the irrigation of fields [1].

The variety of waterwheel applications increased greatly through the Middle Ages. Around 1500, the waterwheel was the most important tool for power generation in Europe and elsewhere. Waterwheels were used to drive elevators for the conveyance of water, ore, and debris out of mines; to drive hammer mills, as well as the large bellows for the air supply of blast furnaces and smelting ovens in the ancient iron works; and, of course, to drive the thousands of grain mills along the rivers. In the 16th century, Leonardo da Vinci made some sketches that are almost recognizable as water turbines as we know them today.

In 1737, the French engineer B.F. Bélidor built a waterwheel with curved blades; in 1738, Daniel Bernoulli (1700-1782) published a book on hydrodynamics in which he developed a theory of waterwheels. In 1754, Leonhard Euler (1707-1783) published a theory of water turbines with wicket gates, although he did not refer to his machinery as turbines (for more on Bélidor, Bernoulli, Euler, and many others, see [1]). After 1770, waterwheels were consistently improved, and wheels made from cast iron or even sheet metal began to appear. Finally, by 1826, a detailed theory of waterwheels existed and some types of speed control were proposed in publications. However, there is no reliable proof of any practical application of such control.

The first step toward a turbine was taken in France by Jean Victoire Poncelet (1788-1867). In 1825, he built a waterwheel with curved blades [2], as Bélidor had done earlier. The curved blades effectively reduced internal hydraulic losses. In addition, Poncelet invented an installation to change the flow (and thus both speed and torque) of what by then resembled a wicket gate (Fig. 1). As seen in the figure, it was adjusted by hand.

At about the same time, several engineers began to apply various designs of wicket gates interacting with the runner. A wicket gate proposed by Euler in 1754 forced the flow in a certain direction, thus reducing the hydraulic losses when entering the runner. As result, the first real turbines appeared. At first, however, they were not known by that name but were called hydraulic gyroscopes or hydraulic impellers. The name *turbine* was probably first used in 1824 by the Frenchman M. Burdin [1]. One of the many improved constructions was a turbine invented in 1837 by Carl A. Henschel (1780-1861) in Kassel, Germany (Fig. 2). In his design, the fixed wicket gate was situated above the runner, where there was already a draft tube, and the flow was regulated by means of a butterfly valve. Henschel's turbine [3] was very common at that time.

In the United States, James B. Francis (1815-1892) improved upon some inventions of his fellow countrymen. This resulted in a turbine with spiral casing, a circular wicket gate (not yet adjustable) placed around the periphery of the runner, and a draft tube. About 1860, the blades of such wicket gates were made adjustable simultaneously, and gradually the many other types of turbines became speed controlled by centrifugal regulators. The further historical development of hydro turbines is described in detail in [1].

Centrifugal Governors: The Flyball Principle

For at least 100 years, the flyball was the only component to control the running speed of hydraulic turbines. Therefore, it makes sense to briefly summarize its history, even though

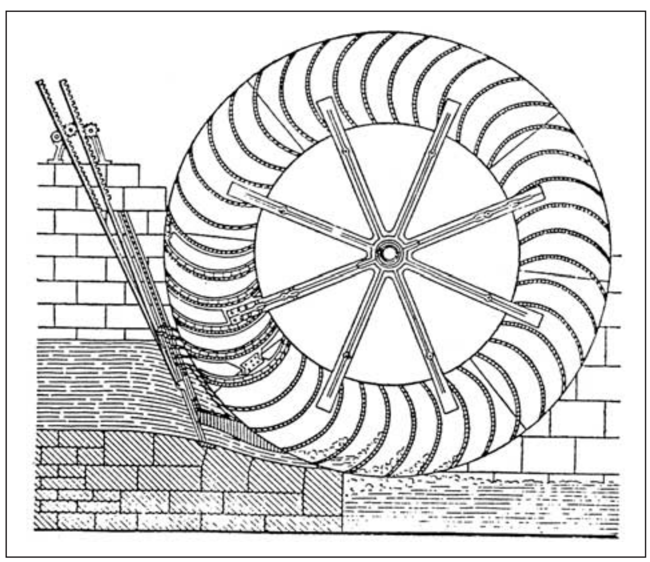

Figure 1. *Poncelet's waterwheel with "wicket gate" (from [2]).*

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water turbines are neither the oldest nor the only prime movers controlled in such a way.

In the 18th century, thousands of windmills were operating in England, the northern part of Europe, and America. These mills became subjects for control mechanisms much earlier than hydro turbines. Some engineers considered the possibility of using closed control loops as we know them today [4]-[7]. The most important development was the flyball principle [8]. Thomas Mead and Stephen Hooper were English engineers who specialized in constructing grain mills. A British patent was issued to Mead in 1787 and another to Hooper in 1789. In his patent specification, Mead called the flyball "a regulator using a new principle." Both inventors designed similar systems to control both the distance between the millstones and their speed, as well as the speed of the vanes [4]-[7].

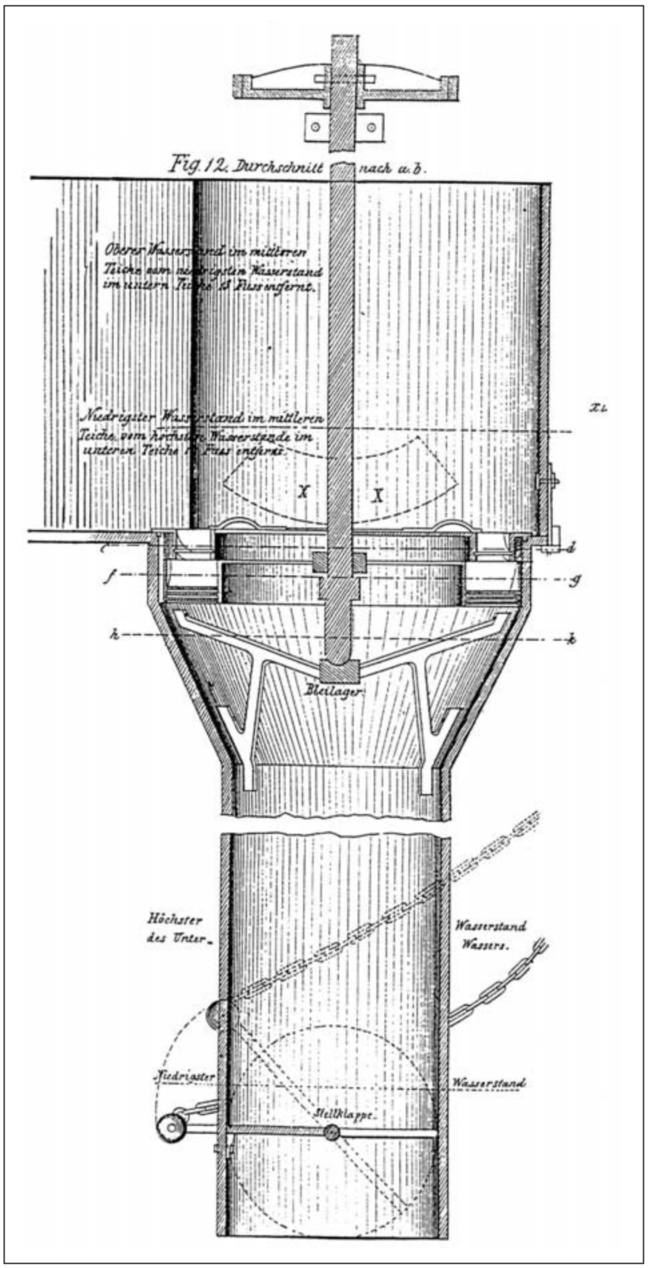

Figure 2. *Henschel's turbine (from [3]).*

The steam engine also appeared during this period of the industrial revolution. James Watt (1736-1819) and his partner Matthew Boulton (1728-1809) sold their first rotative steam engines in 1783. A British patent was issued to them in 1784 detailing the machinery but making no mention of a control system. In 1788, Boulton came across either Mead's or Hooper's flyball regulator in a London grain mill, which was equipped with two Boulton and Watt steam engines. He described the principle in a letter to Watt and proposed it for speed control of their engines. This principle was incorporated successfully, and Boulton's well-known drawing (Fig. 3) shows the first documented centrifugal regulator applied to governing steam engines. The principle soon became well known as "Watt's regulator" (which certainly was not correct). It was discussed in early journals and books and was applied to speed controls of prime movers throughout many decades [4]-[9].

For many years, the term Watt's regulator referred only to the various designs of the flyball component. About 150 years ago, engineers slowly began to investigate its proper-

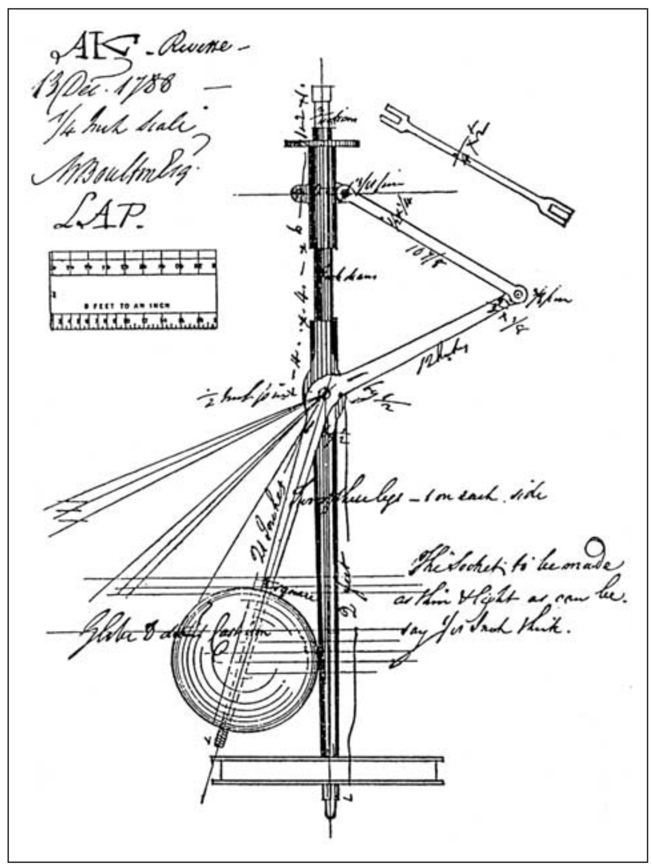

Figure 3. *Boulton's drawing of his centrifugal governor, 1888 (from [6], based on a original drawing [Boulton and Watt, portfolio 714] reproduced with the permission of Birmingham City Archives).*

ties. One learned from the experiences of others, and over time they extended the knowledge base. The fact that one control system worked well but another was almost unstable was believed to be due exclusively to the respective flyball constructions. But engineers soon learned to reduce the oscillations by means of springs, which was a first empirical step in the right direction. Fig. 4 shows such a regulator with quite a strong spring that enabled this device to run faster than others. In addition, the force of the spring helped to move the control mechanism (gate, valve, etc.) of the turbine. The regulator was 90 cm high. Because of this, considerable damping was also caused by the surrounding air. For more historical constructions, see [6].

Early Investigations of Flyball Systems

A flyball controller damped by a spring (see Fig. 4) was a device with simple proportional action that at the time was called uneven, irregular, or static. Most controlled systems also had this property, which obviously caused steady-state control errors. Only Watt's regulator was thought responsible for this misbehavior, and thus it was often regarded as being of no use. "This is not true; the flyball governor is of good use as long as it is applied correctly," stated Franz Reuleaux (1829-1905), a professor in Zurich and later in Berlin, in an important paper [10] in 1859. He systematized the various constructions known at the time and distinguished between static (proportional) and nonstatic (integral) regulators. He also distinguished between direct and indirect transmission of the regulator's movements to the respective actuator (mostly a flap) and described this as very important. Indirect transmissions mainly had integral action. Thus, by plausible considerations, he concluded correctly that static regulators should be combined with indirect transmissions only, and vice versa. However, primarily direct transmission was used at that time. Therefore, a nonstatic regulator was able to avoid control errors in most cases. Consequently, many designs of such regulators appeared one after the other. One possibility for designing a nonstatic regulator was to guide the flyballs along parabolic curves [6]; another was to use constructions like that in Fig. 5 with almost parabolic tracks of the flyballs. Depending on the properties of the controlled systems, the

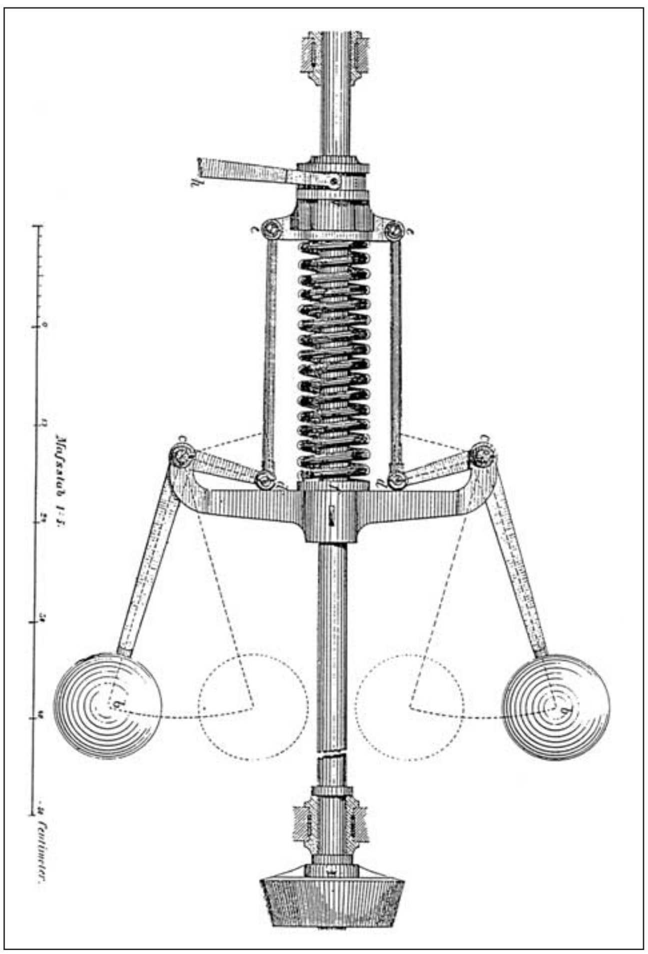

Figure 4. *Centrifugal regulator with spring damping, 1865 (from an old drawing).*

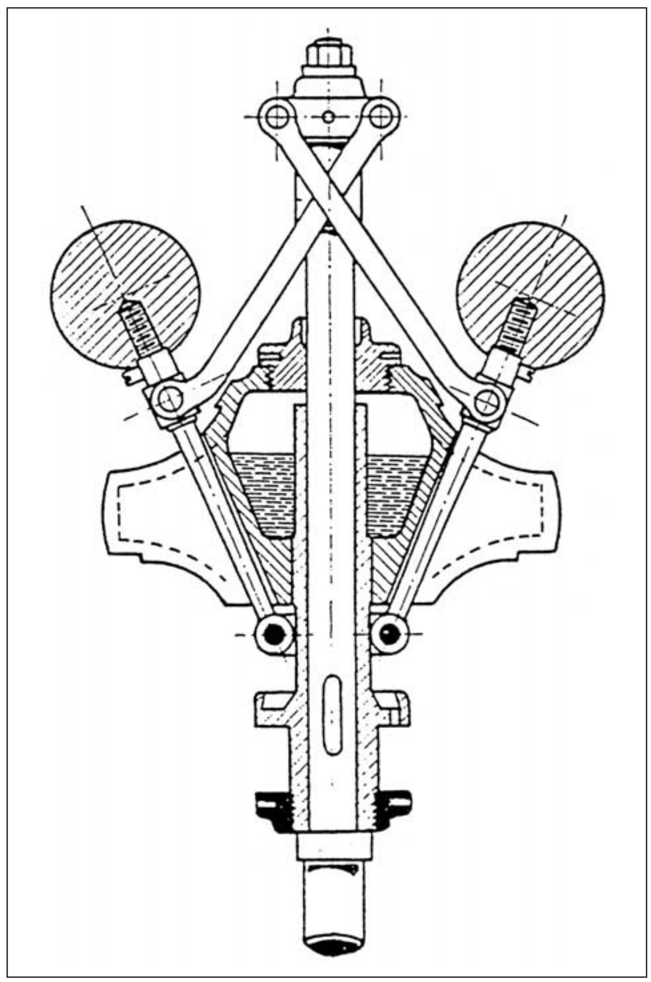

Figure 5. *A nonstatic parabolic regulator, 1880 (from [11], [22]).*

so-called parabolic (integral acting) flyball controllers tended to cause heavy oscillations or even instability. This could be reduced effectively by springs, water- or oil-dashpots, or weights. For the regulator shown in Fig. 5, the damping effect of the weight could be influenced by the level of a liquid filling.

Two years after Reuleaux's publication in 1861, the German engineer J. Lüders wrote a thorough paper [12], [13] in which he proposed and defined an essential characteristic quantity. This quantity was the difference between maximum and minimum speed related to rated speed (degree of irregularity [6]). It was nothing more than the gain of the regulator. It is noteworthy that he calculated this coefficient for some known static governors and showed how to influence this coefficient by details of construction. He also investigated some parabolic regulators. It is even more remarkable that he discussed the qualitative influence of various types of flyball regulators on the behavior of controlled systems.

Lüders certainly guessed the importance of dynamics and stability. However, ten years later, Ludwig Kargl, a professor in Zurich, understood it precisely. The essence of what he wrote in 1871 was: "Until now, we have had no clear knowledge about the influence of governors on machinery. The reason is that the question was still treated as a static problem, whereas it is of the greatest importance in considering the dynamic behavior of the system" [14]. Kargl's assessment of the situation was that the movement of the governor during a disturbance must be investigated. He analyzed static flyball governors and their interaction with controlled systems using linear differential equations. Besides Sir George Biddell Airy and James Clerk Maxwell, whose works he probably did not know of, he was one of the first scientists to recognize the importance of considering closed-loop dynamics.

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It seems noteworthy that seven years before Lüders, on 20 February 1858, a Mr. E. Hunt concluded a letter to the journal *The Engineer* (London), p.169, by stating: "A perfect governor must not be called into action by a change in speed, but must *feel* the cause of such a change, and anticipate its effect, making the necessary adjustment *before* the threatened alteration in speed actually takes place" (see [6]). He was remarkably ahead of his time.

The Feedback Pioneers

Any discussion of feedback pioneers must begin with the famed Sir George Biddell Airy and James Clerk Maxwell. Although their work did not extend to the control of water turbines, they laid the foundation for those engineers who developed such methods a few decades later.

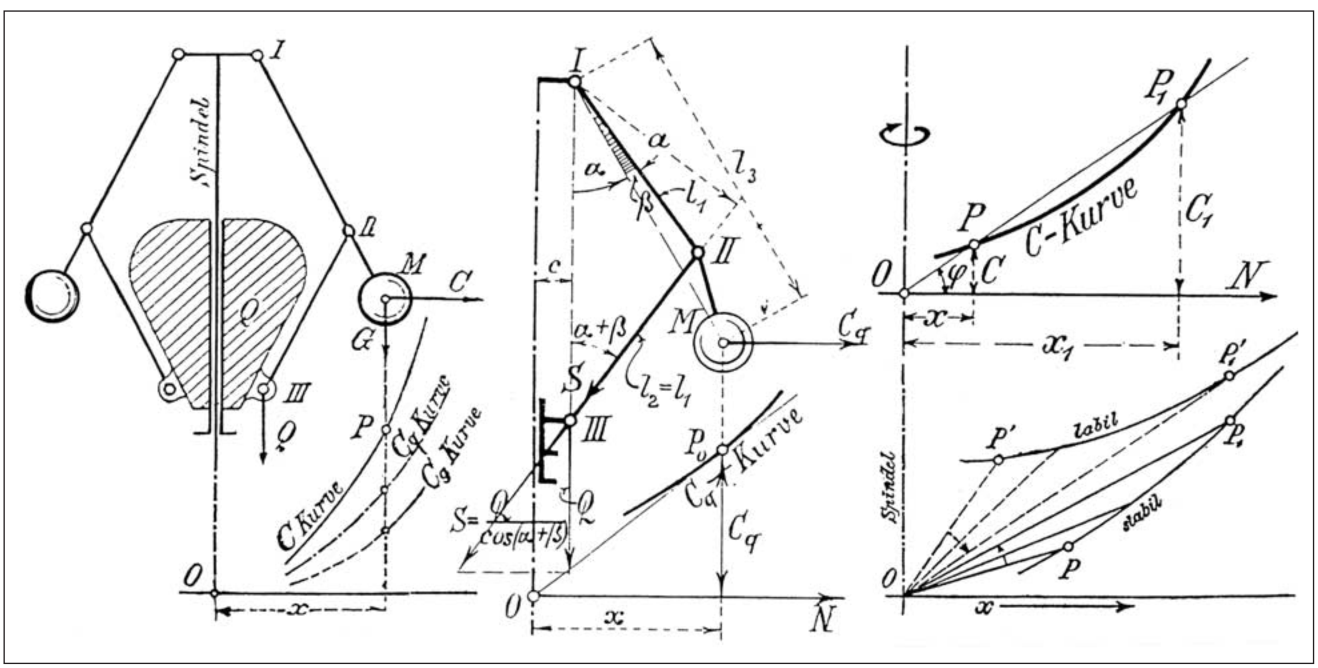

Figure 6. *Definition of Tolle's C-curve (from [11], [22]).*

Airy (1801-1892) was a mathematician, physicist, and "Royal Astronomer"—an all-around scientist. Following his professorship in Cambridge, he became the director of the Greenwich Observatory. In 1840, he designed a governor to achieve constant movement of an astronomic equatorial telescope. In this work, when his system became unstable, he was confronted with the stability problem of closed loops, an experience that led him to serious theoretical considerations [15]. Thus, Airy was the first to investigate theoretically a closed control loop.

Maxwell (1831-1879) carried out the first systematic study of the stability problem about 1867 [15], [16]. He evolved the stability conditions for one third-order control loop and derived a fifth-order differential equation to describe another system. However, he ultimately admitted that he was unable to generally solve the stability problem for fifth- and higher order systems, stating: ". . . but I hope that the subject will obtain the attention of mathematicians." Edward John Routh (1831-1907) of Cambridge, son-in-law of Airy, viewed this task as a challenge. In 1877, he defined the characteristic equation and eventually published his well-known criterion [15], [17].

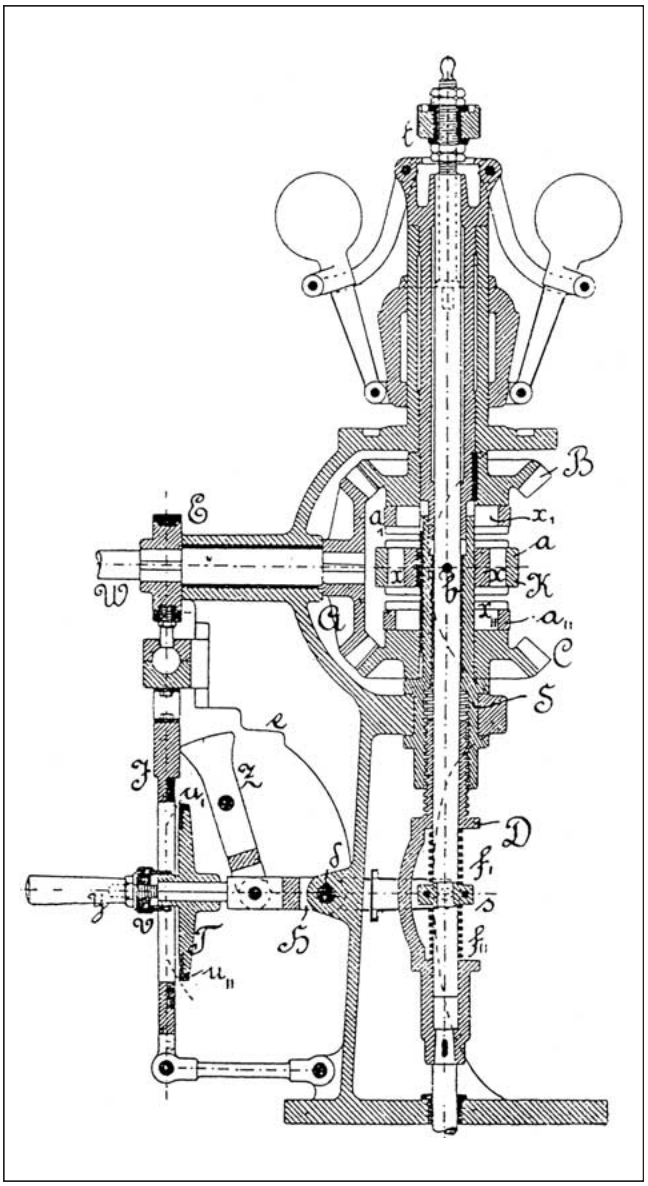

Figure 7. *Pure mechanical governor patent of Proell, 1884 (from [27]).*

In his 1877 paper [18], Iwan Alexejewich Wishnegradski (1831-1895), a professor in St. Petersburg, analyzed a system composed of a rotating prime mover controlled by a directly acting flyball governor. In doing so, he considered the influences of mass, friction, and damping, and he simplified and linearized the mathematical models of the respective components. Like Maxwell, he thus derived a third-order differential equation [6], [19] describing the behavior of the system. In work conducted simultaneously with and independent of Routh, he also defined the characteristic equation representing the homogeneous system. He further proposed some useful values and design factors and discussed their influence on the characteristic equation's coefficients and thus on the dynamic behavior of the loop. In this connection, he stated that the roots of the characteristic equation, namely, the closed loop's eigenvalues (he did not yet call them such), must all have negative real parts. Eventually, he displayed the respective results in stability graphs that were later named after him.

The work [20]-[21] achieved by Aurel B. Stodola (1859-1942) was a milestone in the development of control. Stodola spent 36 years as a professor in Zurich, where he lectured on mechanical engineering. In 1893, he analyzed a high-head hydropower plant, linearized the mathematical models of its components in the operating point, and, because of drastic simplifications, ended up with a third-order model. One important aspect was that he normalized the deviations from the operating point and was the first to define time constants. He soon became aware that his first reductions had gone too far and eventually described the same plant by a seventh-order model. However, he could not solve the resulting characteristic equation, but he correctly stated the necessary stability condition and presumed that there must be a certain relation between the coefficients to guarantee stability. He asked his colleague and professor of mathematics, Adolf Hurwitz (1859-1919), for help, and, in January 1894, he was able to write a letter to Hurwitz thanking him for his new stability criterion [19]. Consequently, Stodola used the Hurwitz criterion to establish guidelines on designing a hydropower plant to guarantee stability and even well-damped transient performance.

Several graphic methods for both analyzing and designing centrifugal governors were developed during the last two decades of the 19th century. The best known and most effective approach [11] was published in 1895 by the German professor Max Ch. Tolle (1864-1945). From construction details of the governor, he calculated two components of the centrifugal force: C_g and C_q. C_g results solely from the mass M of the flyballs; C_q results from Q; that is from the weight of all other masses in the system and from the force of a spring (if there is one) (see Fig. 6). Tolle plotted both these components and their sum as functions of the flyball's distance from the axis of rotation and called this graph C-curves. Thus, the shape of these curves characterized the behavior of the governor. At a certain rotating speed, the centrifugal force C of the flyballs, which is proportional to the distance x, must balance the C-curve $(C_g + C_q)$. Thus, it became obvious whether or not a governor was stable, static, or nonstatic. Rather complicated graphs based on such curves enabled the user to investigate and influence the dynamics of the governor. Remarkably, inertia, friction, and damping effects could be taken into account, and even time series graphs could be constructed. The approach was also published in Tolle's book ([22] and two subsequent editions), which was one of the first textbooks on speed control of driving engines with emphasis on hydro turbines. In this book, Tolle applied his method to a great number of governors and, based on the results, compared them critically. Tolle's method was used for 20 years or more.

Although Airy, Maxwell, Wishnegradski, Stodola, and Tolle were the most important pioneers, many more would follow them, building on the solid foundation they laid. More and more engineers would investigate actual problems of controlling turbines and hydropower plants. What are these problems? Here's just one example. The hydraulic subsystem of a high-head plant composed of surge tank, penstock, turbine, and (sometimes) a tailrace tunnel is a highly nonlinear dynamic system; moreover, it is a nonminimum phase system (an all-pass). Historic low-head plants did not suffer from these properties; however, some contemporary plants in Alpine regions are not easily stabilized at no-load operation before connecting to the grid. Therefore, these days, application of simulation techniques, computer-aided system design, and advanced methods of control theory play an important role [23]-[25].

Mechanical Governors

The early governors were nothing more than the flyball component that acted directly on the turbine's valve or wicket

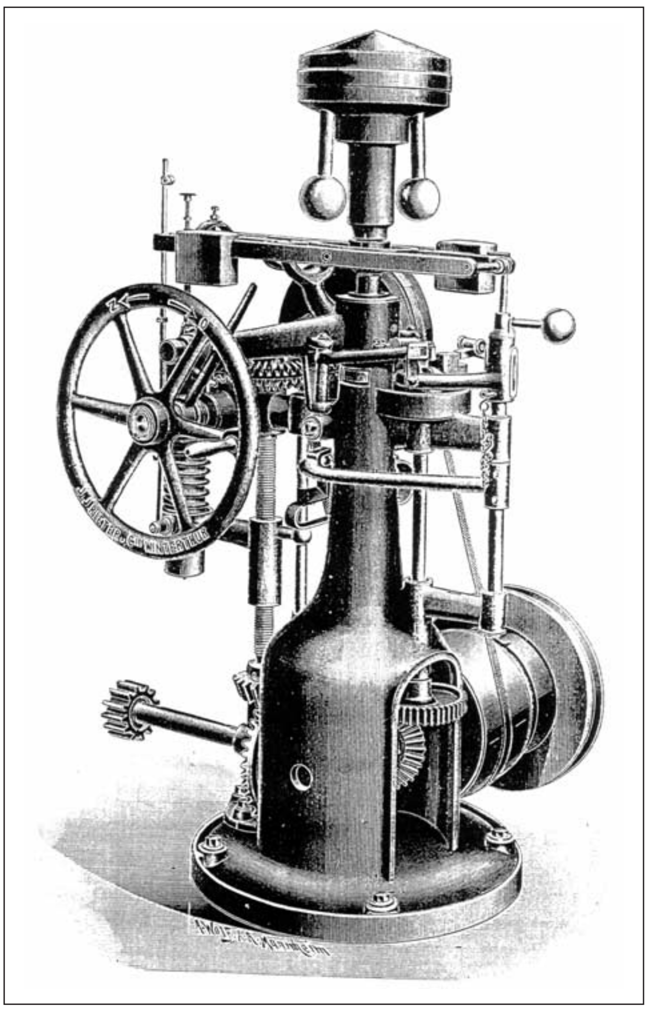

Figure 8. *Mechanical governor of J.J. Riter & Co, Switzerland, 1896 (from [28]).*

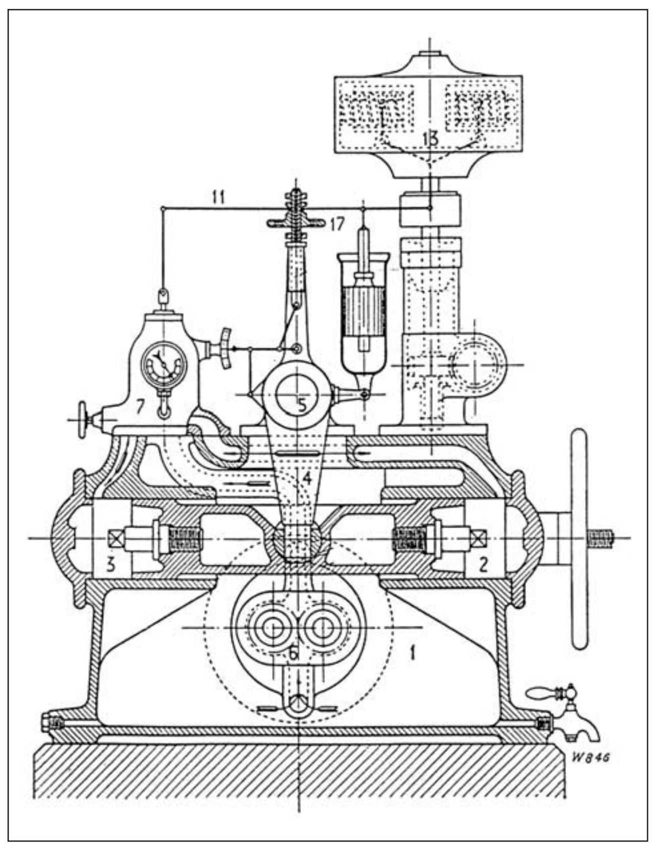

Figure 9. *Universal governor of Escher Wyss, Zurich, 1906 (from [29]).*

gate. The essential new invention around 1880 was the use of power amplification to move the valve or the gates of the turbine. Thus, the servomotor appeared on the stage. The first servo systems were more or less complicated mechanical gears that were called mechanical relays [26] or sometimes differential regulators because they applied differential gears. The idea was to use the turbine's speed and power both to drive the flyball and to move the gates accordingly, as done by the governor designed by R. Proell (Fig. 7). The shaft *W*, driven in some way by the turbine, drives the cogwheels *B* and *C*. *B* drives the flyball; *C* runs loose as long as it is not connected to the coupling *K*. Depending on the actual speed, the flyball moves the innermost vertical stick *b* up or down. The coupling *K* is connected to *b* and is also shifted up or down accordingly. Thus, apart from hysteresis, *K* lifts or lowers part *D* by

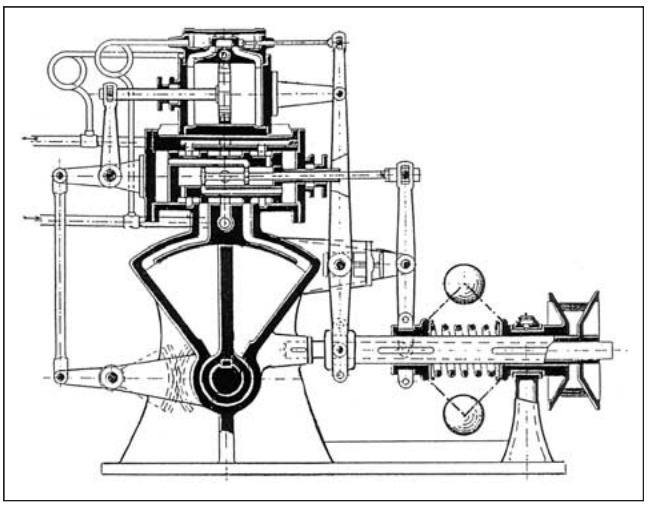

Figure 10. *Sturgess governor, U.S.A., about 1900 (from [30]).*

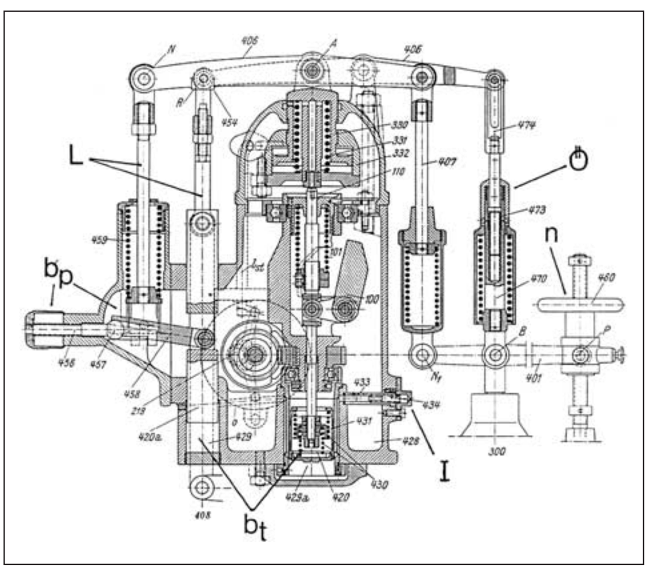

Figure 11. *Pilot unit with integrated flyball sensor, about 1935 (from [31]).*

means of a screw. *D* moves lever *H,* which eventually acts on the gates of the turbine. In describing his invention, Proell [27] used many pages to consider both the amount of power amplification and the dynamic behavior; eventually, he promised stability. However, because of the lack of feedback and the presence of hysteresis, the control loop produced a limit cycle.

The governor in Fig. 8 worked on a similar principle. As an improvement, we can recognize a feedback system composed of a lever and a damper, a principle introduced around 1875.

Differential regulators had been on the market from about 1884 until around 1900. During the same period, however, the first hydraulic piston servomotors were developed, which used the pressure of the upstream water for amplification. Simultaneously, in 1884, the Escher Wyss company of Zurich invented an oil-hydraulic piston servomotor, the principle of which is still in use today. Next, steps were taken to gradually improve the feedback systems by applying springs, throttles, and oil-hydraulic dashpots. As a result, the feedback system was able to achieve not only stability, but also proper dynamic behavior. Thus, the course was set for developing and improving the mechanical oil-hydraulic governor in the 20th century.

The compact governor in Fig. 9 was one of the first standardized so-called universal governors to achieve mass production. The casing, made of cast iron, served as an oil container and housed the oil pump (6) and the servomotor (2,3), together with its control channels. One can recognize the pilot valve (7), the feedback mechanism, the set-point adjuster (17), and the flyball (13) driven via a belt pulley, which is not shown in the figure. The handwheel enabled manual operation of the gates.

Further developments of mechanical governors were no longer concentrated in England, but rather in Germany, Switzerland, France, and the United States. In Europe, the governors were mainly designed and fabricated by the manufacturers of hydro turbines themselves. In the United States, however, special producers of governors were established, such as the still existing Woodward Governor Company, of Rockford, IL, the Lombard Governor Company, and the Sturgess Governor Company. The principle and design of the governor in Fig. 10 produced by Sturgess, for example, differed greatly from the European governors of that time. A significant feature, besides the horizontal axis of the flyball speed sensor, was its sectorized piston, which was directly mounted on the horizontal shaft moving the turbine's wicket gates.

Around 1920, most manufacturers began to combine essential components such as the set-point adjuster, pilot valve and piston, feedback, and parameter settings into a separate unit. This unit was called either a pilot controller or an actuating unit. The advantages of these units were their suitability for mass production and their ability to be combined with servo systems of different capacities. In later years, pilot controllers and main servomotors were completely separated from each other—connected only by oil pipes leading to the servomotor and tow cables or linkages that provided feedback of the piston's movements. The pilot controller in Fig. 11 is a fairly complicated construction that was produced in large numbers. It is remarkable that the flyball speed sensor was situated inside this unit. In the figure, some essential components are indicated: set-point adjuster *n*, feedback mechanism *L* and *O*, the components to achieve permanent and temporary speed droop b_p and b_t, and the oil-throttle *I* to adjust the time constant of b_t. From about 1935 until the 1960s, many incrementally improved versions of this design appeared on the market, the last type appearing in 1964—but mechanical governors were still installed and used for many years after that.

The mechanical governors built after 1930 were engineering masterpieces. These highly sensitive and precise devices may be called the "first-generation" turbine governors. Generally, they had fixed structures with either proportional-integral (PI) or proportional-integral-derivative (PID) action. The control parameters could only be changed by altering the transmission ratio of the linkages, exchanging springs, using new oil-throttle settings, and so on. Therefore, not only was the structure of the control algorithm unchangeable, but each parameter could only be adjusted within a more or less narrow range. These restrictions sometimes caused problems when controlling plants with problematic dynamic properties [25].

Electronic Governors and Digital Systems

It took a long time for mechanical governors to be replaced by electric or electronic pilot units combined with conventional oil-hydraulic servo systems. These "second-generation" turbine governors were characterized by a short transitional phase, but their arrival brought to an end the long and famous era of the flyball principle. The flyball, which was ultimately used as a speed sensor driven by a generator-motor system, was replaced by the electric measurement of rotating speed or frequency.

Electronics now reached the domain of signal processing. Operational amplifiers or transistors combined with condensers, inductors, and resistors in feedback determined the dynamic properties. The control parameters were to be adjusted by means of potentiometers, and the feedback of servomotor stroke was effected also by potentiometers or inductive sensors. This analog technology requires no further discussion. Like their mechanical ancestors, these analog governors still had unchangeable structures of their PI or PID actions with all the same disadvantages.

Although the work of Sir George Biddell Airy and James Clerk Maxwell did not extend to the control of water turbines, they laid the foundation for those engineers who developed such methods a few decades later.

More and more publications such as [32], mainly from universities, propagated digital control by means of microcomputers. The first step away from the analog governor toward the flexible programmable digital controller marked another short intermediate stage: Classical control structures were now implemented into EPROMs. The change of

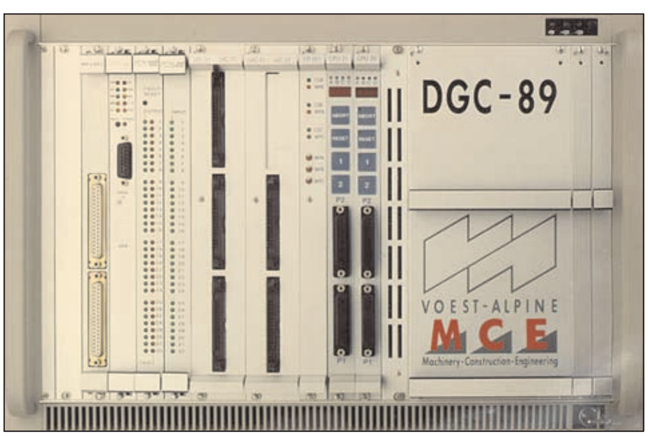

Figure 12. *Digital governor DGC-89 of Voest-Alpine M.C.E., Linz, Austria,1989. (Photograph courtesy of VOEST.)*

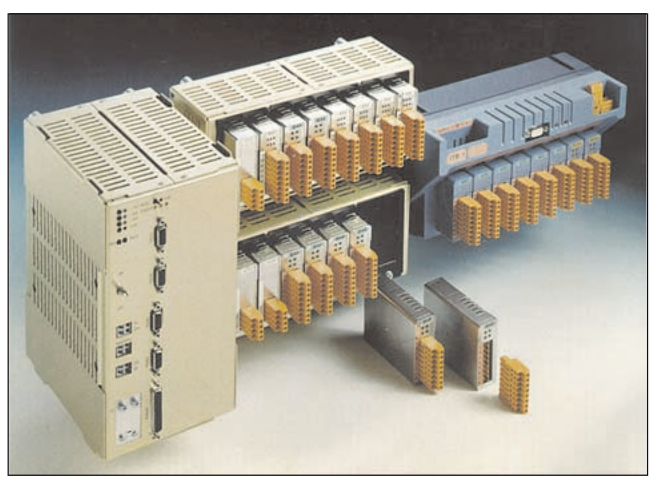

Figure 13. *Turbine controlling system DTL 595 of Sulzer Escher Wyss, Zurich, 1998. (Photograph courtesy of Sulzer Escher Wyss.)*

algorithms was only possible by exchanging or reprogramming of the EPROM. This was certainly no optimal solution; it was, however, an important move.

The contemporary governors of the "third generation" are compact multiprocessor controllers. Fig. 12 shows one of the first designs, for which both the hardware and software were developed by collaborators of the author. Designed for all kinds of closed- and open-loop control and monitoring, it was a modular multiprocessor system with 32-bit processors and a VME-bus structure. A firmware library and a block-oriented language made it possible to implement any configuration and to adapt or change it, if necessary. Programming was done on a PC, as is common today.

The most recent development as part of a construction-kit system is shown in Fig. 13. This sophisticated system provides several additional functions, such as the possibility of determining the optimal relation between wicket gate position and runner blade angle of Kaplan-type turbines, as well as process signal acquisition to observe temperatures, for instance. The enlarged system also allows for superimposed functions of control, supervision, and automation communicating via a fiber-optic bus. In addition, a convenient process visualization feature is available.

Concluding Remarks

We have come a long way from the first centrifugal regulators to mechanical relays and mechanical governors and, finally, to today's technology. These developments were made possible by the contributions of many pioneers. Certainly, at the end of each particular step, our engineering predecessors thought they had reached perfection. Looking at Fig. 13, we probably have the same impression. Who knows?

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