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Sir FREDERICK J. BRAMWELL, F.R.S., President,
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**“The Electrical Regulation of the Speed of Steam-Engines,
and other Motors for Driving Dynamos.”**

By PETER WILLIAM WILLANS.

THE economy of electrically regulating and reducing the speed of motors driving arc lights in series, as light after light is thrown out of circuit, is so obvious, that the Author does not propose to allude to it in this Paper, further than to show a means by which the regulation can be accomplished.

In incandescent lighting, however, although the steadiness and uniformity of the lights are of the utmost importance, and the difficulty of obtaining them, especially in large installations, is great, the necessity for such a governor is, perhaps, not generally recognized, and it is with the regulation of this system of lighting, that the Author proposes mainly to deal in the present Paper.

If dynamos could be made perfectly self-regulating, and centrifugal governors absolutely isochronous, and if the resistance of copper wire and the friction of the motor could be eliminated, electrical governors would still have distinct advantages in their fewer working parts, their absence of friction, their greater compactness, and their capability for easy and complete adjustment. Until, however, perfection is reached in the machines, and especially until a lower price shall allow electrical engineers to use copper freely in the mains, centrifugal governors will permit and even increase irregularities in the lighting, which will disappear with the use of electrical ones.

The Author will first refer briefly to the causes of these irregularities, and then endeavour to show how they may be prevented.

Dynamos have been so much improved of late, by the use of more powerful field magnets, and the consequent reduction in the

number of turns of wire on the armature, that the resistance of the latter is no longer such a disturbing element as it was; and a good result may now be obtained with a first rate mechanical governor, where the lights are placed in the neighbourhood of the machine. The most economical machine, *i.e.*, the pure shunt, is therefore becoming better and better adapted for small variations in the load, and compound machines are less necessary.

Where, however, the mains are long, and laid with some regard to the value of copper, their resistance becomes a factor which it is impossible to neglect. It may be enough to render the action of the best self-regulating machine (unless specially wound for the circuit) very imperfect, and to increase the error in a shunt machine so as practically to prohibit its use if the motor driving it be mechanically governed.

In many cases, moreover, where motive-power is cheap, as for instance with turbines, it would be desirable, for economical reasons, to lay small mains, and to put up with considerable loss in them, were it not that the regulation of the lighting is then almost impossible without some system of adjusting the speed of the dynamo, so as to maintain a constant electromotive force at the point where the current is used, and not where it is generated.

For any particular circuit, of course the resistance of the leads can be taken into consideration, and a compound dynamo specially wound to suit it. But the difficulty of turning out such dynamos commercially is greatly increased by the special winding of each one, and such a system in a large installation would entail the great drawback, that the dynamo wound for one circuit would probably not be adapted for the others, and the advantages arising from the interchangeableness of the units would be lost in consequence. Neither are the magnetic qualities of the iron used in the magnets so well understood as to admit of absolute calculations being made for each and every machine beforehand.

It must not be forgotten that the error which is introduced by the resistance of the leads is of the same nature as, and is aggravated by, the error in the speed of the motor when regulated by an ordinary centrifugal governor.

Assuming that a machine is perfectly compounded in the first instance, but that the resistance of the leads introduces a loss of 7 per cent. in electromotive force when the maximum number of lights is in use, this loss practically disappearing when the lights are at their minimum, the motor should obviously be so regulated that its speed should increase by nearly 7 per cent. as the lights are turned on. A centrifugal governor would so regulate

the speed of the motor, that instead of increasing it would diminish it, probably to the extent of 5 per cent., and the result would be a serious reduction in the power of each individual light.

Another error, in no way allowed for by mechanical governors, arises from the heating of the machine, and from the consequent reduction in electromotive force at the designed speed. Moreover, however carefully these difficulties are considered at first, changes may subsequently be made in the conducting mains or leads of an installation which will upset the most exact compounding: nor can compound machines overcome the difficulties which arise when two or more independent units are connected to the same mains, and it is desired to control the speed of the several units in such a manner that each does its fair share of work. Most of these difficulties disappear with the use of Electrical Governors, and all are thereby reduced in extent and become less formidable.

It is not with any intention of detracting from the credit due to those who have given so much time and thought to the production of compound or self-regulating machines, that the Author brings forward the merits of Electrical Governors; but rather in the hope of going a step further in the same direction, in order to surmount the remaining difficulties of the problem, and to maintain constant light even if the load be very variable and the mains very long.

It should further be mentioned that while the pure shunt machine is at once the simplest to construct and the most economical theoretically, its combination with a motor electrically governed ensures a reduction in speed, and consequently in the losses due to the frictional resistances of the motor, when the lights are not at their maximum. Assuming the variation in speed to reach 15 per cent., as it easily may, the gain due to a corresponding reduction in friction is by no means to be despised, remembering, that in a well-designed installation, it should not be the rule at all times to drive engines and machines at full power.

The Author has thought it advisable to point out his difficulties, which are doubtless familiar to many who have had practical acquaintance with the subject, before proceeding to the description of the governors themselves, the more so as many of the early Electrical Governors appear to have been designed with a view to the maintenance of a constant speed of engine, and, especially as none of these governors have had, so far as the Author has been able to ascertain, any extended practical application.

The earliest allusion to the electrical regulation of motors

driving dynamos, of which the Author is aware, is in Mr. St. George Lane Fox's specification, No. 4,626, 1878.

Within a few days of the date of the above, a patent (No. 4,705, 1878) was taken out in this country by Messrs. Sawyer and Man, of the United States of America. In their specification they describe a cog-bar of T section, arranged to slide in a groove cut in a piece of metal; this piece of metal is pivoted on a standard, and so arranged that, when it is tipped one way or the other, the cog-bar comes into gear with one or other of two pinion-wheels. The wheels are kept constantly revolving in opposite directions, and the cog-bar moves in one direction or the other, according to the direction of rotation of the pinion-wheel with which it is brought into gear for the time being, and it is connected to the steam-valve of the motor. The tipping of the cog-bar is controlled by an electro-magnet placed in the circuit, and this magnet is opposed by a spring, so that when the magnet is overpowered by the spring, the cog-bar is brought into gear with one revolving pinion, and the steam-valve is opened wider, and when the spring is overpowered by the magnet, the cog-bar is brought into gear with the other pinion, and the steam-valve is closed.

In the following year, 1879, Mr. J. D. F. Andrews, in his specification No. 2,321, describes the use of a solenoid for the purpose of regulating the speed of the motor. In this method the coils of the dynamo are wound with separate parallel wires, and an arrangement is effected by which a greater or less number of these wires may be coupled in series, he says—

“According to another method, when the coils of the machine do not consist of separate parallel wires, I introduce into the external circuit a solenoid having an iron core, which is connected to a throttle or other regulating valve of the engine that works the machine, in such a manner, that according as the strength of the electrical current passing through the solenoid is greater or less, the core is caused to move more or less by its attraction, and so, by moving the valve, to regulate the speed of the engine and machine. Instead of applying this apparatus directly to the regulating valve of the engine, it may be applied to vary the outlet of a fluid pumped by the engine, to act on a piston connected to the regulating valve.”

Although nothing further is said about this in his final specification, it is obvious that Mr. Andrews had in contemplation a governor similar to that patented by Mr. Richardson two years later. The Author believes that Mr. Andrews was the first to suggest the use of a fluid relay for actuating the regulating

mechanism so as to leave to the solenoid only the duty of working the valve of the relay cylinder.

In 1881, Mr. John Richardson obtained a patent—No. 288—for an invention “relating to an improved method of, and appliances for, controlling and regulating the speeds of engines employed for driving dynamo-electric machines, which have to be driven at an absolutely uniform speed.”

The first governor described in this patent was an ordinary centrifugal one, driven by an electromotor.

The following is Mr. Richardson’s description of the action of the apparatus:—

“This electromotor is actuated by a portion of the main current which produces the electric light, and its speed varies in relation to the intensity of the said current, so that when the large dynamo-machine which produces the current has reached such a speed as gives the required intensity, the governors at the same time attain sufficient speed to shut off all further admission of steam, and the current is therefore retained exactly at this intensity, and as all changes of intensity, however minute, instantaneously affect the admission of steam, whatever may be the variations of intensity in the current, these are instantaneously rectified by a greater or less admission of steam, thus maintaining the current at a practically uniform intensity.”

Mr. Richardson goes on to describe an electro-magnet which falls in the event of the current entirely failing, its weight being such as to overpower the centrifugal governor.

According to another method of governing, by Mr. Richardson, the centrifugal governor is entirely dispensed with. The stalk of of an equilibrium-valve passes through the valve-casing, and is connected to the core or armature of an electro-magnet placed below. Mr. Richardson says, “When the current passes through the electro-magnet this armature is attracted downwards so as to partially close the admission of steam, and the position of the throttle valve and consequently the admission of steam is regulated according to the intensity of the electro-magnet.”

“The throttle-valve is made of such area that its vertical motion need not be more than a fraction of an inch to give all the variations required from the full power of the engine to an absolute cut-off of the steam.”

In another governor, the core of the electro-magnet acts on a lever connected with, instead of directly to, the throttle-valve.

In 1881 Mr. C. A. Carus-Wilson obtained a patent, No. 568, for various combinations of electro-magnets with speed-governors,

the duty of the electro-magnets being to supplement the action of the centrifugal governor.

Towards the end of the same year, Mr. George Westinghouse obtained a patent, No. 3,409, for an electrical regulator, consisting of a solenoid and a fluid relay, similar in principle to that of Mr. Andrews. The core of the solenoid was attached to a balanced valve, which admitted or released fluid under pressure to or from a cylinder in which was a piston, connected by a rod to the regulating valve of the motor. The fluid under pressure was admitted to the cylinder when the current through the coils of the solenoid was greater than desired. When, on the other hand, it fell below the standard, the fluid was allowed to escape, the relay-piston being brought back by a spring. A small rotary pump, driven from the engine, is shown as a means of obtaining the requisite fluid-pressure.

Probably the friction of the stuffing-boxes was found troublesome in the two governors already alluded to, as in the following year Mr. Richardson took out a patent, No. 941, 1882, for further improvements. After mentioning a governor described in his previous patent, in which a great part, or the whole, of the electric current passes through the governing solenoid, he says—"According to my present invention I connect this solenoid with the valve by fixing the levers under instead of above the valve, to draw the valve downwards instead of forcing it down, and thus get the stalk of the valve in tension instead of compression. By this means its diameter, and therefore its friction in the stuffing-boxes, is very much reduced. This thin stalk I make of steel or of phosphor-bronze, and carry it upwards through the stuffing-box, connecting its upper end by means of a flexible cord or steel band either to the arm of a lever upon the long arm of which I hang a weight, or pass it round a pulley on the opposite side of which I hang a weight, or connect it directly to a strong spiral or other spring, the object being to lift the valve upwards to open it in opposition to the force of the solenoid tending to close it."

In the same specification he mentions a method of winding the solenoid in such a manner that by moving a lever over certain contact-pieces "the solenoid can be varied in intensity, each additional contact-piece bringing into play, or shutting out, an additional coil of wire, thus permitting the speed of the engine to be varied at will according to the work it is set to do." The lever referred to, which is used for varying the speed of the engine, is described and shown as if it were worked by hand, not automatically.

"With currents of lower intensity," Mr. Richardson proposed to use two solenoids placed side by side, through the coils of which "the current could be caused to pass either in series or parallel currents according to circumstances, and the intensity of which can be varied by moving the levers over the contact-pieces as previously described." Mr. Richardson also describes an elastic double diaphragm inserted between two parts of the throttle-valve spindle. Steam from the boiler enters between the two diaphragms by a flexible pipe, so that when the pressure of steam in the boiler increases the throttle-valve spindle lengthens, and so compensates for the increased boiler-pressure. "Could a uniform pressure of steam be depended upon, such an arrangement would be unnecessary in this class of governor, but, as it is well known that boiler pressures do vary considerably, this expedient is used to counteract the same, which it does by the diaphragm expanding and thus partly closing the valve as the pressure rises, and contracting and thus admitting more steam to the engine as the pressure falls." Mr. Richardson further describes a governor in which the core of a solenoid is directly connected to one end of the valve-rod in a well-known arrangement of automatic expansion-gear, for the purpose of varying the point at which the steam is cut off.

The Author is not aware how far any of these methods have been applied practically, but it would be interesting to learn what is the experience with governors of this class, particularly as to the amount of power absorbed in the solenoid, and as to the accuracy of the governing. From his own experience, the Author would have supposed that the direct actuation of the expansion-gear by an electro-magnet was impracticable with any form of magnet which could be economically employed.

In 1883 Mr. Richardson introduced a centrifugal governor, which, on any alteration in the speed of the engine, completes the circuit through an electromotor in one direction or the other, the duty of the motor being to vary the position of the expansion gear.

The governors, to which the Author has alluded, may be divided into three classes: 1st. Those in which an electro-magnet, or an electro-motor, is used, in conjunction with an ordinary centrifugal governor. 2nd. Those in which the armature of an electro-magnet (the coils of which form part of the circuit to be governed) is connected directly to the regulating valve of the engine. 3rd. Those in which an intermediate relay of power is used to increase the power of the electro-magnet. Governors of the first class are necessarily complicated, and combine some of the dis-

advantages both of electrical and of mechanical governors. Those of the second class are, in the Author's opinion, not powerful enough to be depended upon unless very large magnets are used, and considerable power is absorbed in them. It may be well to point out that, when the solenoid core is directly connected to the throttle-valve or expansion-gear, the power available for regulation is not the total attractive force of the coils, but only such an increase or diminution in that force as results from a change in the electromotive force, so small as to be unobjectionable in the lights. It is impossible to avoid friction in the stuffing-boxes, especially when high-pressure steam is used, and half a turn of a nut by a careless man may spoil the lighting, unless there be ample power in reserve.

Governors of the third class, although they have the requisite power to move the regulating mechanism, have not the necessary control over it, on account of the independent action of the parts of the relay. It is evident that, in a governor of this class, each change in the load must entail a double motion of the valve of the relay, or of the part which, in an electrical relay, takes the place of the valve. If the current through the coils increases, the movement of the core calls the relay mechanism into action; and that action continues until the core has returned to its old position. By that time the regulating mechanism may have moved rather too far, and the action described above is repeated, but in the reverse direction. Thus the solenoid core and the regulating-valve of the engine move independently of each other, and it may often happen that while the core of the solenoid is moving in a direction to close the valve, the valve is opening. This independent action must introduce serious irregularities in the lighting, the extent and duration of which will depend on the weight and the speed of the revolving parts of the machinery, as also upon the time it takes for a change in the speed of the dynamo to affect the position of the core of the solenoid. The core of the solenoid may be moved almost instantly when the change in the load takes place, but it may not move back for a considerable interval of time, and during that time the action of the relay mechanism must continue. For these reasons, apparently, Electrical Governors, the need for which has long been recognized, and which were first suggested seven years ago, have until recently only been applied in isolated and experimental instances. Evidently some means are required to ensure the simultaneous action of the core or armature of the electro-magnet, and of the mechanism which actuates the throttle-valve.

In a more recent form of governor designed by Mr. Jamieson,¹ the Author would have expected to find that the friction of the mechanism caused irregularities in the lighting, unless very powerful magnets were employed and considerable power was absorbed in the governor; and he was surprised that Mr. Jamieson insisted on the necessity for a self-regulating dynamo. True, the question was one of lighting ships by electricity, where the error due to the leads is not likely to be so great as on land; and in that class of work the difference in speed which their resistance and that of the armature would otherwise necessitate can be compensated for in winding the magnets with something like certainty. But where electrical regulators are employed it is unnecessary absolutely to fix the speed of the dynamo beforehand.

The Author thinks that the governor mentioned by Mr. Jamieson, which permitted the speed of a Westinghouse engine to increase 25 per cent. must have been an exceptionally bad one. He has made mechanical governors which would control the speed of quick-running engines within 5 per cent.; and there are well-authenticated cases of the normal speed being maintained within 2 per cent. in large engines, but it so happens that for electric lighting constant speed is not usually wanted.

The principal worker at this problem in America has been Mr. Hiram S. Maxim, well known in this country for his new gun, and he has very kindly sent to the Author an account of what he did, from which the following are extracts:—

“In the summer of 1877 I made an electrical governor for controlling the speed of the steam-engine which operated the dynamo-electric machines. This governor operated on the following plan: A powerful electro-magnet, having pole extensions made to fit a copper cylinder or disk, was mounted on an oscillating shaft. This was mounted upon a stand with an arm projecting. This projecting arm controlled the point of cut-off on a Corliss engine in one model made.

“In another model this projecting lever was made to actuate a device which would open and shut the throttle-valve after the manner in which the governor operates on the gates of a large water-wheel; that is, it operated a clutch which determined which way the screw was turned.

“The copper armature was made to rotate at a high velocity between the poles of this electro-magnet and at a constant speed,

¹ Minutes of Proceedings Inst. C.E. vol. lxxix. p. 8.

the electro-magnet being wound with fine wire and connected in multiple arc, the same as the lamps were connected. Of course as the current became too strong the tendency of the copper was to rotate the magnet in the same direction.

"This was opposed by a spring. If the spring was stronger than the tendency of the magnet to rotate with the copper more steam was let on to the engine; if the tendency to rotate was greater than the stress of the spring, then the movement of the projecting arm was such as to partially close the steam off from the engine.

"By reference to a drawing on page 31 of 'Engineering, Jan. 9th, 1885, you will see a regulator which operates practically upon the same principle which mine did. It, however, has the addition of some bevel gears for reversing the motion."

Another of Mr. Maxim's governors was described by him in a letter written to the Editor of 'Engineering,' and published in that journal on March 4th, 1884.

The Author cannot claim, either for himself or for those who have worked with him, an absolute priority in their recognition of the advantages to be expected from this method of governing; but so far as he is aware, he has been the first to make a practical success of it, his method having been adopted in fifty-three instances. His attention was first called to the subject about three years ago by Mr. R. E. Crompton, who mentioned the great need of an Electrical Governor in the case of arc lighting in series, so that the resistance which it was necessary to insert when lamps were switched off could be dispensed with, and economy thereby gained.

As the action of a solenoid or electro-magnet is obviously too delicate, except in very small engines where the power absorbed is not considered, to admit of its direct application for regulating the position of a throttle-valve, the Author suggested that it would be desirable to use, for the actual work to be performed, some relay of power, such as steam or water under pressure in a cylinder, the duty of the governing solenoid being merely to actuate a piston, or other equilibrium valve controlling the supply and discharge of the fluid under pressure. He also suggested that, as the independent action of the piston-valve and piston would inevitably lead to hunting, they should be connected with the regulating solenoid in such manner that the action of the latter on the piston-valve should be neutralized by the motion of the throttle-valve, as the steersman's action is neutralized by the motion of the mechanism connected with the rudder in Mr. M'Farlane Gray's steam-steering apparatus.

He accordingly designed and made the governor shown in Plate 9, Fig. 1. The main principles embodied in this governor have not been subsequently modified, although the details have only been decided after tedious and numerous experiments.

By a coincidence Mr. Wilson Hartnell arrived independently at conclusions very similar to those of the Author; and he showed his designs to Mr. Crompton at about the time the Author's first governor was ready for trial.

Subsequent inventions have been introduced, one by the Author, for the use of electrical relays; and one in the joint names of Hartnell, Willans and Crompton, this latter including some important modifications of Mr. Hartnell's, by which the use of steam as a relay is facilitated; also several methods of winding the solenoid, suggested by Mr. Crompton, in order to compensate for the loss in electromotive force due to the resistance of the leads, without its being necessary to lead the solenoid circuit to the lighting centre. The Author has also introduced a safety arrangement, and a combined potential and current governor, which will presently be described.

So far the relay employed has been water under a pressure of from 10 to 20 lbs. per square inch. The use of water has the advantage of simplicity, and dispenses with stuffing-boxes, which would be necessary if steam were employed. Since the pressure required is not great, nor the quantity of water large, and as, moreover, it may in most cases after passing through the governor be used as feed-water for the boiler, it will probably be employed oftener than the other relays named. About 30 lbs. of water per hour are used in the governor of a 60 HP. engine.

Messrs. Willans and Robinson were on the point of adopting the electric light when the Author's first patent was taken out, and he carried out all the experiments connected with the governor at their factory; but it was Mr. Crompton's recognition of the necessity for a regulator which would act from a distance, which first directed the Author's attention to the subject, and afterwards induced him to persevere with the experiments in spite of practical difficulties.

Throughout these experiments he endeavoured to keep the following points in view:—

1st. The necessity for very prompt action and even greater sensitiveness than is required in a governor for constant speed; for an increase in the current through the solenoid is often the first indication to the governor that the speed of the motor requires not merely to be brought back to a standard, but to be reduced.

2nd. The necessity for great power in the relay, combined with the minimum of friction in the electric regulating portion of the mechanism.

3rd. The power to control the potential automatically at any desired point in an incandescent installation, and not merely in the engine-room, as in the case of mechanical governors.

4th. The power so to regulate the speed of two or more units of an installation, that the work is properly divided between them.

5th. The easy and accurate adjustment of the apparatus while at work so as to avoid any errors due to friction, such as occur in centrifugal governors, in which the revolving balls act on a stationary spring, the tension of which is adjusted at will.

Proceeding now to the diagrams, Plate 9, Fig. 1 represents the experimental governor already alluded to. It was made during the winter of 1882-83, and employed regularly during the following winter for controlling the potential for one hundred incandescent lights at Messrs. Willans and Robinson's works at Thames Ditton. In this governor the core Q is attracted by the coils of the solenoid S, and this attraction is balanced by the spiral spring X, from which the core is suspended by the rod R; on the rod R is a washer Y; against this washer a roller A presses. This roller is carried on the end of a differential lever A B C, the lever being prolonged in order to carry a balance weight Z, which can be regulated in such a manner that the roller A presses more or less on the washer Y. The point in the lever C is connected to the rod joining the piston in the relay-cylinder W to the throttle-valve T. To the point B is connected the rod of the piston-valve P. If the current through the coils of the solenoid S increases, the core Q is drawn further into them, and the piston-valve P is also moved down. The water under pressure is thus allowed to act on the under side of the water-piston, entering the cylinder by way of the pipe E, the annular space between the two pistons of the piston-valve placing this pipe in communication with the passage K. The water-piston moves up, closing the throttle-valve T, which is shown as a piston working in a perforated cylinder. The water above the water-piston is discharged by the upper of the two pipes F F. As the water-piston moves up, the point C in the differential lever moves up with it, and to a less degree the point B also, the motion continuing until the piston-valve P is brought back to its original position, when the mechanism comes to rest with the throttle-valve in its new position, until some fresh disturbance in the circuit or in the steam-pressure calls it again

into action. The movement of the two points A and C in the lever is practically simultaneous, so that to the observer the point B appears to be a fixed fulcrum on which the lever rocks, the movement necessary to open the passage being very small.

In the experimental governor the point A was not connected rigidly to the rod R, because it was thought desirable to obtain reliable information as to the friction of the piston-valve under ordinary conditions. The weight Z was so regulated that it just overpowered the weight of the roller A, but the slightest increase in friction was shown, whenever more steam was required, by the washer Y leaving the roller as the core moved up, when the spring overpowered the diminished current. By carefully observing the behaviour of different valves the details of the apparatus were determined experimentally, and the friction of the piston-valves was eventually reduced to about $\frac{1}{10}$ oz.

The rod of the piston-valve passed in this case through a bush, H, at the lower end of the valve cylinder, and it was impossible entirely to get rid of the friction of this rod; but in all subsequent governors the piston-valve has been worked from above, the rod passing down a tube of sufficient height to ensure that the water discharged from the relay-cylinders shall not pass over it, thus dispensing with stuffing-boxes (Plate 9, Fig. 2).

The principal difficulty at first encountered was that of "hunting," and many devices were tried to get over it, such as dash-pots to prevent the core moving quickly, and cocks on the water-pipes to cause the relay-piston to move slowly. These devices prevented, to some extent, actual hunting or oscillation of the throttle-valve after a change in the load, but they introduced a worse evil in the slower action of the governor whenever a large change in load necessitated a rapid alteration in the position of the throttle-valve, the result of this slower action being a considerable temporary alteration in the intensity of the lights. It was long before the Author realized the necessity for absolutely simultaneous movement of the regulating mechanism and the relay-piston, and that the dash-pots were only useful so far as they prevented the core of the solenoid from moving more quickly than the relay-piston. Eventually all dash-pots were abandoned, and the hunting was overcome by increasing the area of the passages between the piston-valve and relay-cylinders, so that the throttle-valve could move as quickly as, and as nearly as possible in unison with, the core of the solenoid. Improvements in the piston-valve, whereby its friction was reduced to a minimum, also conduced to similar results; for, as the governor cannot be

called into action until the increase in the current through the solenoid coils is sufficient to move the core and overcome the friction of the valve, any decrease in the friction must render the action of the governor more prompt and delicate.

In this first governor the Author thought it desirable to try the experiment on a small scale, and the relay-cylinder was only 1 inch in diameter. This proved sufficient for the regulation of the engine, the power of which was 15 I.H.P., but all subsequent relays have been made much more powerful to provide for contingencies.

Plate 9, Fig. 2 shows the governor ordinarily employed for controlling the position of the throttle-valve. In this type of governor the travel of the core is necessarily the same as that of the relay-piston, and it is not therefore suitable for any but small ranges of position in the regulating mechanism. Otherwise the arrangement is a most convenient one, for the throttle-valve water-cylinder and solenoid are placed one above the other in the same axial line. The friction of joints and pins is avoided, the piston-valve being connected directly to the core of the solenoid. No packing is required on the piston-valve rod as it passes down the tube, H, which is high enough to prevent any splash of water. The piston-valve in this type of governor works inside the hollow rod of the piston in the relay-cylinder. The water enters the annular space between the two pistons of the piston-valve by a port, E, in the side of the cylinder, and a recess, V, in the relay-piston which is made deep on purpose. From this recess the fluid under pressure passes through a drilled hole into the interior of the hollow piston-rod, the position of the hole being such that it is never covered by the valve. The passages leading from the piston-valve to the two ends of the relay-cylinders are so arranged that the relay-piston follows the motion of the piston-valve, and comes to rest when it overtakes it. The passage which is covered and uncovered by the upper piston of the piston-valve leads to the bottom of the relay-cylinder, and the one which is similarly covered and uncovered by the lower piston of the piston-valve leads to the top. If the current through the coils of the solenoid S increases, the core Q is drawn further into them. The piston-valve P moving down allows the water under pressure to pass through the pipe E to the upper side of the relay-piston by the passage K. The relay-piston then moves down until it overtakes the piston-valve P and closes the passage K. The water from the under side of the relay-piston passes away above the upper piston of the piston-valve by the passage K, and afterwards by the flexible pipe M. The core and relay-piston move

practically together, and it requires close observation to see that they are not rigidly connected. The throttle-valve, which is in this case also of the piston type, is double, the ports admitting steam being formed in the side of the sleeve in which the double throttle-valve works.

The diagram shows the valve half-open, the upper piston of the throttle-valve covering one-half of the port. On the slightest increase of current through the solenoid coils the throttle-valve descends, its upper piston closing still further the steam inlet. If, on the other hand, the current decreases, the throttle-valve rises and admits more steam. But should the belt break, or the main lead from the dynamo be severed, so that the current entirely fails, or in case of a short circuit of sufficient magnitude to reduce the difference of potential at the terminals of the machine by 50 per cent. or 60 per cent., the spring draws the core up altogether, and steam is then shut off by the lower piston of the piston-valve.

The governors are usually made with six coils wound with No. 30 wire. When these are coupled six in series they give the necessary pull with an electromotive force of 100 volts; when coupled three in series and two parallel they give the same pull with 50 volts; and when coupled two in series, three parallel, they give the same with 33 volts. The resistance of each coil is about 55 ohms, making 330 ohms when all are in series, and the current due to 100 volts is about 0.3 ampere. The electrical energy absorbed in the solenoid is thus 32 watts, or about one-half that of a twenty candle-power Swan lamp; such a solenoid is capable of controlling with ease the throttle-valve of an engine of 60 I.H.P.

The method of winding the six coils separately is very convenient, as it renders the same governor suitable for any electromotive force between 30 and 100 volts, whilst at the same time the cooling surface is increased.

The curve in Plate 9, Fig. 4, shows the pull on the core of the solenoid when the current due to an electromotive force of 100 volts is passing through the coils. The pull is shown by the horizontal ordinates at each $\frac{1}{2}$ inch of the stroke; the attractive force of the coils commences to be felt by the core just before the latter enters them; it reaches its maximum when the core is about half in and half out, and diminishes from that point until it disappears when the centres of the coils and of the core coincide. The part of the travel of the core which is used by choice for regulation is near the apex of the curve. Here the pull is practically constant for a distance equal to the travel required by the throttle-valve, and as the position of the apex of the curve does not differ appreciably

with varying currents, its height, and consequently the mean electromotive force to be maintained, can readily be determined by adjusting the mean pull of the spring by the wing nut at the top. The diagonal line cutting the curve represents the tension of the opposing spring. This diagonal line only coincides with the pull of the spring at one point in the travel of the core.

It is well understood that, in a centrifugal governor, it is not advisable absolutely to balance by the spring at every position the force exerted by the revolving weights, because such perfect balancing would cause "hunting," the parts of the governor influenced by the speed flying off on the slightest change to one end or other of their travel. The same applies in a less degree to the electrical governor. When the core is moved from its position of repose by a change in the intensity of the current through the coils of the solenoid, the spring must do something more than balance the pull due to the normal electromotive force when the core is drawn further into the solenoid, and something less than balance the pull due to the normal electromotive force when the core is allowed by the reduction in current to recede from the coils under the influence of the spring. In other words, as the load is increased there must be a slight fall in electromotive force, and as it is diminished there must be a slight rise in electromotive force. This is shown graphically by the diagonal line representing the tension of the spring crossing the curve representing the pull on the core.

Variations in the tension per inch of elongation of the spring determine the accuracy and stability of the governor; the greater the tension per inch, the more the curves cross and the greater is the stability; the less the tension, the more nearly the curves coincide and the greater is the accuracy. It is obvious that, as the tension of the spring is fixed, the pull on the core must be slightly reduced when the core is at its highest position, and slightly increased when the core is at its lowest; it must, in fact, decrease as the throttle-valve opens, until the opposing forces are balanced at A, and increase as the throttle-valve closes, until they are balanced at B.

The Author has made numerous experiments on various cores, to determine their best proportions for this particular purpose. Obviously the lighter the core the less is the chance of overshooting the mark by its own momentum when sudden changes occur; but on the other hand, it is very undesirable to reduce its section much, for, as the point of saturation is approached, a greater change in electromotive force is necessary to raise the pull due to the normal

electromotive force, and so balance the pull of the spring in the new position of the throttle-valve.

The inside diameter of the coils in the experimental governor was $2\frac{1}{2}$ inches, and the length of the winding of the solenoid was 6 inches. The series of curves in Plate 10, Fig. 10, have been taken at 100 volts, and show the pulls in each position for cores of different lengths but of the same section and extreme diameter. The lengths of the cores varied from 12 inches to 4 inches, the length of the winding being the same in all cases. The maximum pull for each core is shown by the curve Plate 10, Fig. 11; and the percentage of the length of core outside the winding, when the pull is greatest, by Plate 10, Fig. 12. But these curves do not indicate the best results attainable with a given section of core. A core 12 inches long was made of gas-pipe, turned and bored, to remove scale, and to get rid of weight other than that of the iron. This core was tested, and then reduced inch by inch in length, so that the same piece of iron was used throughout the series of experiments shown by the curves, Plate 10, Figs. 10, 11, and 12, and the relative pulls for different lengths of core may be taken as fairly accurate. The curves in Plate 10, Fig. 13, are for cores of varying sections, but all 10 inches long; in Plate 10, Fig. 14, they are for cores of different sections, but of the same diameter and length; they show the maximum pull for varying electromotive forces from 10 volts upwards; with the core eventually decided on, the alterations in pull between 90 volts and 110 volts are proportional as nearly as possible to the square of the current.

As the proportions of the cores were improved, the variation in current through the coils, and consequently in electromotive force, represented by the fall to A and the rise to B (Plate 9, Fig. 4), was reduced. In practice a total range of electromotive force of 2 per cent. to 3 per cent. of the normal has been found sufficient to give stability, and even less than that where the total range of power has not been the total which the throttle-valve allowed. By adjusting the set screws S_1 S_1 (Plate 9, Fig. 2), the position of the coils with relation to the mean position of the core can be readily varied, and by this variation a result is obtained equivalent to the use of a spring of greater or less tension per inch of elongation. That is to say, the two curves do not then cross exactly at the apex. If the coils are moved down, the upper part of the solenoid curve is used, and the curves more nearly coincide; and if the coils are moved up, the lower half is used, and they cross at a greater angle than when they cross at the apex.

Thus the mean electromotive force, and the variations in electro-

motive force throughout the travel of the throttle-valve, can both be adjusted with the greatest nicety; and if the variation in power does not require the whole of the travel of the throttle-valve to be used, that part of the travel usually required can be arranged to be the part in which the governor can regulate most accurately.

In order to give stability to the governor, it is almost always desirable that the curves should cross, but the extent to which they must cross depends mainly upon the suddenness of the changes to be expected in the load. When the angle at which the curves are to cross has been determined, the error in electromotive force at the extremities of the travel of the throttle-valve is in proportion roughly to the length of the travel, and anything which reduces that travel, leaving other things as before, conduces to the accuracy of the governor.

To meet exceptional cases, where it is necessary to use the whole range of power which the travel of the throttle-valve allows, and where at the same time great quickness in action and great accuracy—by which is meant a variation of less, say, than 2 per cent. in electromotive force—are required, the Author has devised a preliminary regulating valve. The duty of this valve is to prevent any great difference of pressure on the two surfaces of the throttle-valve, and to avoid the necessity for that valve moving from one extreme of its stroke to the other. By taking care that, under different loads, the difference in pressure is approximately constant, the travel of the throttle-valve will be very small, and thus accuracy will be gained in the governing without sacrifice of stability. A convenient way of arranging this regulating valve is shown in Plate 9, Fig 5. The Author has shown this valve in connection with the governor in Fig. 1. Steam from the boiler is conducted through the pipe D into a recessed part of the cylindrical casing I, in which is a trunk-piston having holes J J in its sides. This piston is carried by a rod G, which passes through a stuffing-box at the lower end of the casing; on this rod is a washer N, which compresses a spiral spring O, when the piston rises. If the piston rises, the holes J J, moving into the bored part of the casing I, are closed; if the piston descends, they pass further into the recessed part of the casing, and are opened wider. The upper end of the casing I is connected by a small pipe U with the engine side of the throttle-valve of the electric governor. The lower end of the casing I forms part of the steam-pipe from the boiler to the engine; a pipe L connects it with the throttle-valve of the electric governor. The tension of the spring O determines the excess-pressure of the steam outside the electric

governor over that in the steam-chest, or engine side of the governor. If the excess of pressure is greater than desirable, the piston in the casing I moves up and reduces it by closing the holes J J.

Where two or more units in an installation work independent circuits, but all receive steam from one boiler; and where one unit may need the full boiler-pressure at the same time that others require a comparatively low one, the advantage of employing a valve of this kind on the pipe leading to the motor of each unit is very great, for it entirely obviates the necessity for accuracy in the boiler-pressure, the only consideration then being a sufficient pressure for the unit which has at the time the heaviest load. The balancing valve, as it may be termed, serves as a rough preliminary governor, the actual electrical governor putting the finishing touch to the regulation. This valve has not in any case so far proved to be necessary, nor is it likely that in ordinary cases it will; but it is a comparatively simple method of arriving at almost absolute accuracy.

Plate 9, Fig. 6, shows the governor in use at the Swan and Edison Company's installation at Victoria Station. The action of this governor is similar in principle to the experimental governor, Fig. 1. The point in the differential lever which is moved by the solenoid is marked A, that connected with the piston-valve B, and that with the relay-cylinder and throttle-valve C.

Plate 10, Fig. 15, was prepared from readings taken between the hours of 5 P.M. and 9 P.M., during one evening at the above installation (see also Table on next page). The upper line shows the electromotive force. The middle line represents the steam pressure, and the lower line the current.

As the load comes on gradually and is taken off gradually, the steam-pressure in the boiler is usually allowed to rise during the early part of the evening, and to fall later on as the load decreases. In order to show the action of the governor under changes in steam-pressure, the pressure was allowed to vary considerably between 6.15 and 7.30 P.M., the load being fairly constant during that time. It will be seen that the electromotive force was hardly affected by these changes, the total variation being from 120 volts to 121 volts. No special precautions were taken, and the governor was not adjusted during the evening.

The delicacy of the action of this governor will be understood from the fact that the variation in speed during each revolution, of which the influence cannot be perceived on the lights or on the potential indicator, is readily noticed by watching the core of the

Time.	Current in Am- peres.	E.M.F. in Volts.	Steam in Boiler.
P.M.			Lbs. per Sq. In.
5.20	230	120	85
5.40	295	120	85
6.0	400	120	100
6.15	485	120	100
6.30	485	120.5	105
6.35	485	120	100
6.44	485	120	101
6.48	485	120	97
6.53	485	121	105
7.2	485	120	100
7.6	485	120	95
7.30	500	120	100
8.0	444	120	95
8.20	420	120	90
8.40	390	120.5	90
8.45	390	120.5	85
9.0	390	120	85

governor, which perceptibly moves with each stroke of the engine. The Author, thinking at first that this must be due to vibration and not to the changes in the current through the solenoid, suspended a second core and spring similar to the one in the working governor alongside it, from a point in the same engine, but there was no motion in this second core. He then watched the behaviour of the core in the second or reserve engine, when the current generated by the first engine was passing through the solenoid from the main, the reserve engine itself standing, and found that the oscillations of the core were quite regular and as apparent as in the engine at work, and were evidently due to the change in the current during each revolution. It was thus made evident that changes in the electromotive force, much too small for the eye to detect in the lights, were enough to actuate the governor.

The Author has alluded to certain improvements in the piston-valves which greatly reduced their friction; the valve shown in Plate 9, Fig. 3, is one of them. However carefully these valves were made, if the two pistons were turned to fit throughout their length, they showed a tendency to press on one side of the cylinder in which they worked more than on the other, and the friction arising from this being considerable, a change in electromotive force was needed to move the valve. This difficulty was eventually overcome by recessing each of the two pistons of the piston-valve, thus reducing the surface upon which the pressure could act, and at the same time rendering it less likely that it would act in one direction more than another.

Plate 9, Fig. 7, shows an arrangement of governors suitable for actuating the expansion-gear of powerful engines. The travel of the solenoid is in this case also $\frac{1}{2}$ inch, but the arrangement of differential levers permits of a 6-inch stroke for the relay-piston. The grip which such a cylinder has upon the mechanism, and the great power available, renders this arrangement very suitable for expansion gears; and it is likewise suitable for automatically throwing in or out resistances, in order to obtain a constant difference of potential between two points in a circuit through which a variable current passes. The power and delicacy of this apparatus are best illustrated by the following figures:—

The mean pull of the coils on the core is 2 lbs.; this corresponds with the centrifugal force acting on the revolving balls in a speed-governor. The friction of the regulating mechanism is about $\frac{1}{5}$ oz., and the power available for actuating the expansion gear is upwards of 500 lbs. exerted through 6 inches.

The position of the regulating mechanism of the engine being adjusted by each of these governors, so as to maintain an approximately constant current through the coils of the regulating solenoid, it follows that for incandescent lighting these coils must form a shunt circuit between the positive and negative mains; but for arc lighting in series the main or a part of the main current must pass through them, the object in that case being to maintain a constant current independent of the resistance of the circuit for the time being.

The advantage of such a governor is very great, for the revolutions and the coal consumption are reduced almost in the same proportion as the number of lights, instead of its being necessary to insert resistances to take the place of the lamps thrown out and so burning the same amount of coal. A governor of this class has been successfully applied at the Ordnance Survey Office at Southampton for regulating the current used for electrotyping, and there are doubtless many other cases where it will prove useful.

The Author has so far referred to those Electric Governors which have been employed for the regulation of the speed of motors driving dynamos, to maintain either a constant electromotive force or a constant current, but these are not the only purposes for which they may be used.

Another purpose is the automatic introduction of resistances into a circuit, the current in which is generated by an engine whose speed cannot well be altered to suit the necessities of the lighting; as, for instance, where the currents in several distinct circuits of varying length and resistance are all generated by one engine.

In such cases it is obviously impossible to govern the engine to suit every circuit, but the electromotive force may be maintained constant in the engine room, and a governor of this class may be employed to insert or cut out resistances, to ensure the resistance of the mains of any particular circuit bearing always the same proportion to the resistance of the lamps in use in that circuit.

The Author will now consider a class of installation, which is probably the most difficult of all to govern, namely, one in which several independent units generate currents which are collected in a single pair of mains. This method permits of the use of a number of comparatively small units, and renders subsequent additions to the installation easy. It also very much reduces the engine-power necessary to be kept in reserve; for if, say, four engines of 100 I.H.P. be used instead of one engine of 400 I.H.P. a single reserve engine of 100 I.H.P. is all that need be provided, whereas, for the larger machinery another engine of equal size must be available. The five smaller engines would indeed have far greater reserve power practically. In the event of a double breakdown, three-fourths of the maximum power would be still available in the smaller units, while a double breakdown would entail total darkness in the large one. There is, however, some difficulty in so regulating the speed of several units, as to ensure that each shall do its fair share of work and no more, and it would appear to be beyond the power of any centrifugal governor, unaided, to solve the problem. The Author understands that this difficulty has given Mr. Edison much trouble in New York.

Plate 9, Fig. 8, shows a *regulator*, which not only maintains a constant potential, but provides also that the unit which it governs shall not generate more than a predetermined current, the quantity of which can be readily varied. In this governor two solenoids and cores A and B are used. The throttle-valve, hydraulic cylinder, and piston-valve, are the same as in Plate 9, Fig. 2; but instead of the valve being connected directly to the core of a solenoid, it is suspended from a point X in a bar, the two ends of which are connected to two points, A¹ and B¹, of the respective cores. The solenoid A is wound as a shunt coil, and its duty is to control the position of the piston-valve, and consequently the electromotive force, as previously described. The solenoid B is wound with the whole or part of the main current, generated by the unit which the duplex governor controls, and it has no effect on the throttle-valve unless the current generated by that unit is greater than desired. Until then, the point B¹ is practically fixed,

the spring drawing the core up against a stop B^2 . The spring is so adjusted that when the current approaches its maximum the core of the solenoid B moves down, and the throttle-valve is closed by the action of the piston-valve and hydraulic cylinder. Thus the shunt coils of the governors may all be connected to the mains, and yet the speed of each unit be so controlled by the series coils of its governor as to do its fair share of work. Shortly, the position of the point A^1 determines the potential, and that of B^1 the current; each point moves independently of the other, and each is capable of the finest adjustment, the potential by the screw A^3 , and the current by the screw B^3 .

If the leads of the units are all connected in or near the engine-room, the shunt coils of the governors are practically connected to the mains, but it is desirable that each solenoid should be connected to the circuit of its own unit. This is shown in Fig. 9 for two units. The "A," or shunt solenoids, are in each case connected to the terminals of the machine, while the main leads pass round the "B" solenoids before they join the mains. Assuming that at certain times unit No. 1 can do all the work required, unit No. 2 may be completely disconnected by breaking its circuit say at Y , and then shutting off steam; but it can be started again at any time, and its potential brought up to the standard by its "A" solenoid before completing the circuit again.

The same method is of course applicable to any number of units. It may often be necessary, instead of connecting the circuits of the several units in the engine-room, to run the leads from the dynamo or dynamos forming each unit direct to a lighting centre, in the manner advocated by Mr. Crompton on the score of economy in leads, when the Victoria installation was designed. In such cases it is desirable to govern each unit from its own lighting centre, so as to maintain a constant difference of potential between the mains at that point rather than in the engine-room. This may be done readily by bringing a pair of small wires to the solenoid from the lighting centre. The resistance of these wires is of no importance, as they form part of the circuit of the solenoid, in which the power absorbed is inconsiderable.

Another method, suggested by Mr. Crompton, is to wind the solenoids, with two coils acting in opposition, the one a shunt direct from the terminals of the machine, while the opposing coil is composed of a few turns carrying the main current. The effect of these series turns is inappreciable when the current is very small, and the electromotive force practically the same at

the lighting centre as at the machine; but as the current increases, the series coils, acting in opposition to the shunt, render it necessary that the latter should become more powerful in order to affect the throttle-valve, and consequently more steam is admitted to the engine, until the required rise in electromotive force takes place.

The Author has used the word "throttle-valve" by choice in describing many of these governors, but it will be understood from the description of Plate 9, Fig. 7, that they can be adapted to any ordinary form of expansive gear. If the duplex solenoids are employed in combination with the differential lever arrangements shown in Plate 9, Fig. 1 and Fig. 7, the point X in the bar between the two cores must be connected to the point "A" in the differential lever.

In this Paper the Author has only described those forms of his governor which have been made, with the exception of the duplex governor, the action of which can be foreseen. Those in which electrical relays are used have for many purposes considerable advantages, but the principle is the same in all, namely, the employment, in conjunction with a regulating electro-magnet or solenoid, of a relay of power for working the throttle-valve, the mechanism of the relay being so connected with that of the regulating solenoid, that for each position of the core there is a corresponding position for the throttle-valve, the motion of the one affecting the other as if they were rigidly connected.

The Paper is illustrated by numerous diagrams, from which Plates 9 and 10 have been engraved.

Fig: 10.

Curve of Pull of Cores of Various Lengths, but all of same diameter and Section.

Fig: 11.

Curve of Maximum Pull of Cores of Various Lengths.

Fig: 12.

Curve of Percentage of Length of Core outside the winding at the point of Maximum Pull.

Fig: 13.

Curves of Cores of same Length and external diameter but of various Sections; With 100 Volts and varying positions.

Fig: 14.

With varying E.M.F.

Fig: 15.