A control system for a variable valve timing apparatus that changes a valve timing of an internal combustion engine using a motor which is controlled by operating a switching element includes: an oil temperature estimating portion; a substrate temperature estimating portion; and a current limit controller. The oil temperature estimating portion estimates a temperature of lubricating oil of the engine. The substrate temperature estimating portion estimates a temperature of a substrate to which the switching element is mounted based on the temperature of the lubricating oil. The current limit controller limits a current flowing through the switching element based on the temperature of the substrate in a manner that a temperature of the switching element is restricted from exceeding a predetermined upper limit value.
FIG. 4

101
CT>T1?

YES

CALCULATE ΔT RELATIVE TO CT

LOAD

ΔT

ENGINE SPEED

BOT=CT+ΔT

104

OT(i)=OT(i-1) × a + BOT × (1-a)

105

BST=OT(i) - [ST(i-1) - CT] × b

106

ST(i)=ST(i-1) × c + BST × (1-c)

107

RETURN

102

103

NO
FIG. 5

1. CURRENT LIMIT CONTROL

2. ST > UPPER DETERMINATION VALUE?
   - NO
   - YES
   - execute CURRENT LIMIT CONTROL

3. ST < LOWER DETERMINATION VALUE?
   - NO
   - YES
   - STOP CURRENT LIMIT CONTROL

RETURN
FIG. 7

ST ESTIMATION

CT > T1?

YES

CT > T1?

NO

CALCULATE COMBUSTION TEMPERATURE

LOAD

COMBUSTION TEMPERATURE

ENGINE SPEED

\[ \Delta T = \{\text{COMBUSTION TEMPERATURE} - OT(i-1)\} \times f \]

BOT = CT + \Delta T

OT(i) = OT(i-1) \times a + BOT \times (1-a)

BST = OT(i) - \{ST(i-1) - CT\} \times b

ST(i) = ST(i-1) \times c + BST \times (1-c)

RETURN

OT(i) = CT
FIG. 9

MOS TEMPERATURE ESTIMATION

CT > T1?

YES

CALCULATE ΔT RELATIVE TO CT

ΔT

LOAD

ENGINE SPEED

BOT = CT + ΔT

OT(i) = OT(i-1) × a + BOT × (1-a)

BST = OT(i) - [ST(i-1) - CT] × b

ST(i) = ST(i-1) × c + BST × (1-c)

ΔMOST = MOS CURRENT × d

ΔMOST(i) = ΔMOST(i-1) × e + ΔMOST × (1-e)

MOS TEMPERATURE = ST + ΔMOST

RETURN
FIG. 10

CURRENT LIMIT CONTROL

MOS TEMPERATURE > UPPER DETERMINATION VALUE?

YES -> EXECUTE CURRENT LIMIT CONTROL

NO -> MOS TEMPERATURE < LOWER DETERMINATION VALUE?

YES -> STOP CURRENT LIMIT CONTROL

RETURN
FIG. 11

- COOLING WATER TEMPERATURE (CT)
- ENGINE SPEED
- LOAD
- COMBUSTION TEMPERATURE
- INCREASE IN OIL TEMPERATURE (ΔT)
- OIL TEMPERATURE (OT)
- SUBSTRATE TEMPERATURE (ST)
- MOS CURRENT
- INCREASE IN MOS TEMPERATURE (ΔMOST)
- MOS TEMPERATURE
- CURRENT LIMIT FLAG

- BASE OT (BOT)
- OT
- BASE ST (BST)
- ST

- UPPER LIMIT GUARD VALUE
- UPPER DETERMINATION VALUE
- LOWER DETERMINATION VALUE

- TIME

Graph showing various parameters over time with specific indicators and values.
MOS TEMPERATURE ESTIMATION

CT > T1?

Yes

CALCULATE COMBUSTION TEMPERATURE

LOAD COMBUSTION TEMPERATURE

ENGINE SPEED

\[ \Delta T = (\text{COMBUSTION TEMPERATURE} - \text{OT}(i-1)) \times f \]

\[ \text{BOT} = \text{CT} + \Delta T \]

\[ \text{OT}(i) = \text{OT}(i-1) \times a + \text{BOT} \times (1-a) \]

\[ \text{BST} = \text{OT}(i) - [\text{ST}(i-1) - \text{CT}] \times b \]

\[ \text{ST}(i) = \text{ST}(i-1) \times c + \text{BST} \times (1-c) \]

\[ \Delta \text{BMOST} = \text{MOS CURRENT} \times d \]

\[ \Delta \text{MOST}(i) = \Delta \text{MOST}(i-1) \times e + \Delta \text{BMOST} \times (1-e) \]

MOS TEMPERATURE = ST + \Delta \text{MOST}

RETURN

FIG. 12
CONTROL SYSTEM FOR VARIABLE VALVE TIMING APPARATUS

BACKGROUND

Conventionally, a variable valve timing apparatus is known, which is mounted in an internal combustion engine for a vehicle. Due to the variable valve timing apparatus, a valve timing (opening and/or closing timing) is changed for an intake valve and/or an exhaust valve, in order to increase engine output power, to improve fuel consumption ratio, to decrease emission of harmful components contained in exhaust gas, and so on.

In most of the variable valve timing apparatuses, which have been put in a market, a rotational phase (a camshaft phase) of a camshaft with respect to a crankshaft is changed by an electric motor or oil pressure so as to change the valve timings of the intake valve and the exhaust valve driven by the camshaft.

According to a variable valve timing apparatus having an electric motor as a driving source, for example, as disclosed in Japanese Patent No. 4,678,545 (US 2010/0019712 A1), a current supplied to the motor is increased to be larger than an usual value in a period started when the engine is started and ended when a temperature of lubricating oil of the engine reaches a predetermined value. Thus, the responsiveness of the variable valve timing apparatus is restricted from becoming worse when the temperature of lubricating oil is relatively low.

When the engine is operated with a high load, the temperature of lubricating oil may increase to 130°C. In this case, temperatures of components lubricated by the oil and a temperature of component located adjacent to an oil passage through which the oil flows may be raised to or around 130°C. Moreover, because many oil passages are provided in an engine head, the variable valve timing apparatus mounted to the engine head and a motor drive circuit driving the variable valve timing apparatus may be in a high temperature state.

The motor drive circuit has a switching element such as MOSFET for controlling the motor, and the switching element easily generates heat. If a large current flows through the switching element in the state where the motor drive circuit is in the high temperature state, the temperature of the switching element may exceed an upper limit value such as 150°C. At this time, the switching element is overheated.

SUMMARY

According to an example of the present disclosure, a control system for a variable valve timing apparatus that changes a valve timing of an internal combustion engine using a motor which is controlled by operating a switching element includes an oil temperature estimating portion, a substrate temperature estimating portion, and a current limit controller. The oil temperature estimating portion estimates a temperature of lubricating oil of the internal combustion engine. The substrate temperature estimating portion estimates a temperature of a substrate to which the switching element is mounted based on the temperature of the lubricating oil estimated by the oil temperature estimating portion. The current limit controller limits a current flowing through the switching element based on the temperature of the substrate estimated by the substrate temperature estimating portion in a manner that a temperature of the switching element is restricted from exceeding a predetermined upper limit value.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects, features and advantages of the present disclosure will be more apparent from the following detailed description made with reference to the accompanying drawings. In the drawings:

FIG. 1 is a schematic view illustrating a control system for a variable valve timing apparatus according to a first embodiment of the present disclosure;

FIG. 2 is a schematic perspective view illustrating the variable valve timing apparatus;

FIG. 3 is a timing chart for explaining a current limit control based on a temperature of a substrate according to the first embodiment;

FIG. 4 is a flow chart illustrating a process of estimating the temperature of the substrate according to the first embodiment;

FIG. 5 is a flow chart illustrating the current limit control according to the first embodiment;

FIG. 6 is a timing chart for explaining a current limit control based on a temperature of a substrate according to a second embodiment;

FIG. 7 is a flow chart illustrating a process of estimating the temperature of the substrate according to the second embodiment;

FIG. 8 is a timing chart for explaining a current limit control based on a temperature of a MOSFET according to a third embodiment;

FIG. 9 is a flow chart illustrating a process of estimating the temperature of the MOSFET according to the third embodiment;

FIG. 10 is a flow chart illustrating the current limit control according to the third embodiment;

FIG. 11 is a timing chart for explaining a current limit control based on a temperature of a MOSFET according to a fourth embodiment; and

FIG. 12 is a flow chart illustrating a process of estimating the temperature of the MOSFET according to the fourth embodiment.

DETAILED DESCRIPTION

Embodiments of the present disclosure will be described hereafter referring to drawings. In the embodiments, a part that corresponds to a matter described in a preceding embodiment may be assigned with the same reference numeral, and redundant explanation for the part may be omitted. When only a part of a configuration is described in an embodiment, another preceding embodiment may be applied to the other parts of the configuration. The parts may be combined even if it is not explicitly described that the parts can be combined. The embodiments may be partially com-
combined even if it is not explicitly described that the embodiments can be combined, provided there is no harm in the combination.

[0023] The present disclosure is applied to, for example, a variable valve timing apparatus for an intake valve.

First Embodiment

[0024] A first embodiment will be explained with reference to FIGS. 1-5.

[0025] A driving power of an internal combustion engine 11 is transmitted by a timing chain (or a timing belt) 13 from a crankshaft 12 to a camshaft 16 for an intake valve as well as to a camshaft 17 for an exhaust valve via respective sprockets 14 and 15. A variable valve timing (VVT) apparatus 18 of an electric motor-driven type is provided at the rotational speed of the intake valve. A rotational phase (camshaft phase) of the camshaft 16 with respect to the crankshaft 12 is changed by the VVT apparatus 18, so that a valve timing (opening timing and/or closing timing) for the intake valve (not shown), which is driven to open and close by the camshaft 16, is controlled.

[0026] A cam angle sensor 19 is provided at an outer periphery of the camshaft 16 so as to generate a cam angle signal for every predetermined cam angle in accordance with the rotation of the camshaft 16. A crank angle sensor 20 is provided at an outer periphery of the crankshaft 12 so as to generate a crank angle signal for every predetermined crank angle in accordance with the rotation of the crankshaft 12.

[0027] An outline structure for the VVT apparatus 18 will be explained with reference to FIG. 2. The structure of the VVT apparatus 18 should not be limited to that shown in FIG. 2, but may be modified in various ways.

[0028] A phase variable mechanism 21 of the VVT apparatus 18 is composed of an outer gear member 22 having an internal gear coaxially arranged with the camshaft 16, an inner gear member 23 having an external gear coaxially arranged with the camshaft 16 inside of the outer gear member 22, and a planet gear member 24 arranged between the outer and inner gear members 22 and 23 and engaged with each of them. The outer gear member 22 is integrally rotated with the sprocket 14, which is rotated in a synchronized manner with the crankshaft 12, while the inner gear member 23 is integrally rotated with the camshaft 16. The planet gear member 24 is rotated around the inner gear member 23, while the planet gear member 24 is engaged with both of the outer and inner gear members 22 and 23, so that rotational force of the outer gear member 22 is transmitted to the inner gear member 23. At the same time, when an orbital speed of the planet gear member 24 with respect to the rotational speed of the outer gear member 22 is changed, the rotational phase (the camshaft phase) of the inner gear member 23 with respect to the outer gear member 22 can be adjusted.

[0029] The engine 11 has an electric motor 26 for changing the orbital speed of the planet gear member 24. A rotational axis 27 of the electric motor 26 is coaxially arranged with the camshaft 16, the outer gear member 22 and the inner gear member 23. A supporting shaft 25 for the planet gear member 24 is linked with the rotational axis 27 of the electric motor 26 via a connecting rod 28, which is extending in a radial direction from the rotational axis 27. According to the above structure, the planet gear member 24 is rotated at the supporting shaft 25 while moving around (an orbital movement) an outer periphery of the inner gear member 23, in accordance with the rotation of the electric motor 26. A motor rotational angle sensor 29 is provided at the electric motor 26 (FIG. 1) so as to generate a motor rotational angle signal for every predetermined rotational angle in synchronization with the rotation of the electric motor 26. The rotational angle as well as rotational speed of the electric motor 26 is detected based on output signals from the motor rotational angle sensor 29.

[0030] The outer gear member 22, the inner gear member 23 and the planet gear member 24 are so structured that the camshaft 16 is rotated in a normal operation at a speed, which is a half of the rotational speed of the crankshaft 12. The rotational speed of the electrical motor 26 is adjusted with respect to the rotational speed of the camshaft 16 (which is rotated at the half speed of the crankshaft 12 in the normal operation), so that the valve timing (that is, the camshaft phase) for the intake valve is controlled.

[0031] When the valve timing is not changed, the rotational speed of the electric motor 26 is set at the speed of the outer gear member 22 (that is, the half of the rotational speed of the crankshaft 12). In other words, the speed of the orbital movement of the planet gear member 24 is controlled to be equal to the rotational speed of the outer gear member 22, so that a difference of the rotational phase between the outer and inner gear members 22 and 23 is held in a status quo and thereby the valve timing (the camshaft phase) is maintained as it is.

[0032] When electrical power supply to the electric motor 26 is cut off, the rotational axis 27 of the electric motor 26 is rotated in synchronization with the outer gear member 22. Namely, the rotational speed of the electric motor 26 may be made to be equal to the rotational speed of the outer gear member 22 (that is, the half of the rotational speed of the crankshaft 12).

[0033] When the valve timing is changed, the rotational speed of the electric motor 26 is changed with respect to the rotational speed of the outer gear member 22 in order that the orbital moving speed of the planet gear member 24 is changed with respect to the rotational speed of the outer gear member 22. As a result, the difference of the rotational phase between the outer and inner gear members 22 and 23 is changed to adjust (change) the valve timing (the camshaft phase).

[0034] For example, in case of advancing the valve timing, the rotational speed of the electric motor 26 is changed to be higher than the rotational speed of the outer gear member 22, so that the orbital moving speed of the planet gear member 24 is changed to be higher than the rotational speed of the outer gear member 22. As a result, the rotational phase of the inner gear member 23 is advanced with respect to the outer gear member 22. Namely the valve timing (the camshaft phase) is advanced.

[0035] On the other hand, in case of retarding the valve timing, the rotational speed of the electric motor 26 is changed to be lower than the rotational speed of the outer gear member 22, so that the orbital moving speed of the planet gear member 24 is changed to be lower than the rotational speed of the outer gear member 22. As a result, the rotational phase of the inner gear member 23 is retarded with respect to the outer gear member 22. Namely the valve timing (the camshaft phase) is retarded.

[0036] As shown in FIG. 1, outputs of the above mentioned various sensors are inputted into an engine control unit (hereinafter also referred to as ECU) 30. The ECU 30 is composed of a micro-computer and carries out various kinds of engine control programs which are stored in ROM (a memory device), to thereby control fuel injection amount for a fuel
injection device (not shown) and ignition timings for an injection device (not shown) depending on engine operating conditions.

[0037] The ECU 30 calculates, during engine operation, an actual rotational phase (an actual camshaft phase) of the camshaft 16 with respect to the crankshaft 12, based on the output signals from the cam angle sensor 19 and crank angle sensor 20. The ECU 30 further calculates a target camshaft phase depending on an operational condition of the engine. Then, the ECU 30 calculates a target motor rotational speed, based on a deviation between the target camshaft phase (a target valve timing) and the actual camshaft phase (an actual valve timing) and based on the engine rotational speed. A signal for the calculated target motor rotational speed is outputted to an electrical motor driving unit (also referred to as ECU) 31. The ECU 31 carries out a feedback control for a power-supply duty ratio (a power-supply control amount) to the electric motor 26, so that a deviation between the target motor rotational speed and the actual motor rotational speed may become smaller. As a result, a feedback control is carried out in such a way that the actual camshaft phase is controlled to be closer to (and finally equal to) the target camshaft phase. The above function of the ECU 31 may be included in the ECU 30.

[0038] The ECU 31 controls the motor 26 of the VVT apparatus 18, and is attached to the VVT apparatus 18 or is placed near the VVT apparatus 18 which is mounted to the engine 11. The ECU 31 has a substrate 33, and a metal oxide semiconductor field effect transistor (MOSFET) 32 is mounted to the substrate 33 as a switching element which is operated for controlling the motor 26.

[0039] The ECU 30 (or the ECU 30 and the ECU 31) executes routines of FIGS. 4 and 5. Specifically, the temperature of lubricating oil of the engine 11 (oil temperature) is estimated based on an operation condition of the engine, and the temperature of the substrate 33 (substrate temperature) is estimated based on the estimated oil temperature. Further, a current limit control is performed to limit a current flowing through the MOSFET 32 (MOS current) based on the estimated substrate temperature, in a manner that the temperature of the MOSFET 32 (MOS temperature) is restricted from exceeding a predetermined (permissible) upper limit temperature such as 150°C.

[0040] Because the substrate temperature is changed by receiving influence from the oil temperature, the substrate temperature can be estimated accurately based on the estimated oil temperature. Moreover, because there is a certain correlation between the substrate temperature and the MOS temperature, the temperature of the MOSFET 32 can be restricted from overheating by limiting the MOS current based on the estimated substrate temperature in a manner that the MOS temperature does not exceed the permissible upper limit temperature.

[0041] Specifically, as shown in the time chart of FIG. 3, while the temperature of cooling water CT of the engine 11 is lower than or equal to a predetermined value T1, that is when the oil temperature OT is changed by following the cooling water temperature, the estimation value of the oil temperature is set to be the same as the cooling water temperature (or a value set by mathematically processing the cooling water temperature.

[0042] Then, while the temperature of cooling water CT of the engine 11 is higher than the predetermined value T1, that is when the oil temperature OT becomes higher than the cooling water temperature, an increase ΔT in the oil temperature with respect to the cooling water temperature (an increase of the temperature of lubricating oil) is computed, for example, using a map based on an operation condition such as rotation speed or load of the engine 11.

[0043] A base oil temperature BOT is obtained by adding the increase ΔT in the oil temperature to the cooling water temperature CT, and the oil temperature OT is estimated by calculation mathematically processing the base oil temperature BOT, so as to smooth a variation in the oil temperature OT. Thereby, the oil temperature can be accurately estimated by considering the increase in the oil temperature with respect to the cooling water temperature even when the oil temperature becomes higher than the cooling water temperature.

[0044] Furthermore, a base substrate temperature BST is calculated based on the estimated oil temperature and the cooling water temperature, which represents a temperature in an engine compartment, and the substrate temperature ST is estimated by calculation mathematically processing the base substrate temperature BST. Thereby, the substrate temperature can be accurately estimated by considering both of the oil temperature and the cooling water temperature.

[0045] At a timing t1 of FIG. 3, at which the estimated substrate temperature ST becomes higher than a predetermined upper determination value, the current limit control is executed, in which the MOS current is limited by a predetermined upper limit guard value in a manner that the MOS temperature does not exceed the permissible upper limit temperature. For example, the predetermined upper determination value is set to be slightly lower than the substrate temperature when the MOS temperature becomes equal to the permissible upper limit temperature.

[0046] Thereafter, at a timing t2, at which the substrate temperature ST becomes lower than a predetermined lower determination value, the current limit control is finished by stopping the restriction of the MOS current. For example, the predetermined lower determination value is set to be lower than the predetermined upper determination value by a predetermined hysteresis.

[0047] The current limit control based on the substrate temperature is performed by the ECU 30 (or the ECU 30 and the ECU 31) according to the routines of FIGS. 4 and 5. The processing of each routine will be described hereinafter.

[0048] A routine of the substrate temperature (ST) estimation illustrated in FIG. 4 is repeatedly executed at a specified cycle while the ECU 30 is ON. When the routine is activated, at t01, it is determined whether the cooling water temperature CT of the engine 11 detected by a sensor (not shown) is higher than the predetermined value T1. The predetermined value is set to a temperature when the oil temperature becomes higher than the cooling water temperature, for example.

[0049] If it is determined that the cooling water temperature CT is lower than or equal to the predetermined value T1 at t01, the estimation value of the oil temperature OT is set to be the same value as the cooling water temperature or a value provided by mathematically processing the cooling water temperature at t02 represented by a formula of OT(i)=CT.

[0050] If it is determined that the cooling water temperature CT is higher than the predetermined value T1 at t01, the increase ΔT of the oil temperature with respect to the cooling water temperature is calculated at t03, using a map based on the engine operation condition such as engine speed and load. The map is provided in advance based on experimental data and design data, and is stored in the ROM of the ECU 30.
Furthermore, the increase $\Delta T$ of the oil temperature may be corrected according to at least one of outside air temperature, intake air temperature, ignition timing, air-fuel ratio, valve timing, and so on.

[0051] Then, the base oil temperature $BOT$ is obtained by adding the increase $\Delta T$ of the oil temperature to the cooling water temperature $CT$, at 104 represented by a formula of $BOT = CT + \Delta T$

[0052] Then, the present-time oil temperature $OT(i)$ is estimated using the last-time oil temperature $OT(i-1)$ and a correction efficient “a” for the base oil temperature $BOT$ at 105 represented by a formula of $OT(i) = OT(i-1) \times a + BOT \times (1-a)$. The processes 103, 104, 105 correspond to an oil temperature estimating portion 41 which is included in the ECU 30 or the EDU 31. Then, the base substrate temperature $BST$ is obtained using the present-time oil temperature $OT(i)$, the last-time substrate temperature $ST(i-1)$, the cooling water temperature $CT$, which represents a temperature in an engine compartment, and a reflection rate “b” at 106 represented by a formula of $BST = OT(i) - ST(i-1) \times CT \times b$.

[0053] Then, the present-time substrate temperature $ST(i)$ is estimated by mathematically processing the base substrate temperature $BST$ using the last-time substrate temperature $ST(i-1)$ and a correction coefficient “c” at 107 represented by a formula of $ST(i) = ST(i-1) \times c + BST \times (1-c)$. The processes 106, 107 correspond to a substrate temperature estimating portion 42 which is included in the ECU 30 or the EDU 31.

[0054] A routine of the current limit control illustrated in FIG. 5 is repeatedly executed at a specified cycle while the ECU 30 is ON, and processes 201, 202, 203, 204 may correspond to a current limit controller 43 which is included in the ECU 30 or the EDU 31. When the routine is activated at 201, it is determined whether the estimated substrate temperature $ST$ is higher than the predetermined upper determination value. For example, the upper determination value is set at a temperature slightly lower than the substrate temperature when the MOS temperature becomes equal to the permissible upper limit temperature.

[0055] When it is determined that the estimated substrate temperature $ST$ is lower than or equal to the predetermined upper determination value at 201, the routine is finished without performing the subsequent processes.

[0056] When it is determined that the estimated substrate temperature $ST$ is higher than the predetermined upper determination value at 201, the current limit control is conducted at 202 to limit the MOS current with the predetermined upper limit guard value so that the MOS temperature does not exceed the permissible upper limit temperature. Furthermore, the VVT apparatus 18 (motor 26) is controlled to change the camshaft phase to a limit position (for example, the maximum retard position) of the movable range of the VVT apparatus 18 compulsorily. The MOS current may be limited by prohibiting a reference position learning in which the present-time camshaft phase is learned as a reference position (for example, the maximum retard position).

[0057] Then, at 203, it is determined whether the substrate temperature $ST$ is lower than the predetermined lower determination value. For example, the lower determination value is set as a temperature lower than the upper determination value by a predetermined hysteresis.

[0058] When it is determined that the substrate temperature $ST$ is higher than or equal to the lower determination value at 203, the current limit control is continued by returning to 202.

[0059] Then, it is determined that the substrate temperature $ST$ is lower than the lower determination value at 203, the current limit control is finished at 204 to stop the limiting of the MOS current.

[0060] According to the first embodiment, the oil temperature of the engine 11 is estimated based on an engine operation condition etc., and the substrate temperature is estimated based on the estimated oil temperature. When the estimated substrate temperature becomes higher than the upper determination value, the current limit control is performed to limit the MOS current with the upper limit guard value so that the MOS temperature might not exceed the permissible upper limit temperature. Thus, the MOSFET 32 can be prevented from being overheated. Moreover, a temperature sensor can be eliminated which detects the oil temperature, the substrate temperature, or the MOS temperature, so the cost can be reduced.

[0061] Generally, a change speed of the substrate temperature is slower than a change speed of the MOS temperature. Therefore, a difference (hysteresis) between the upper determination value and the lower determination value can be made smaller when the current limit control is executed by comparing the substrate temperature with the determination value. Thus, the current limit control is restricted from being frequently switched between the ON state and the OFF state (hunting). The valve timing (camshaft phase) and the engine output can be restricted from being varied by reducing the hunting.

Second Embodiment

[0062] A second embodiment will be described with reference to FIGS. 6 and 7.

[0063] The ECU 30 (or the ECU 30 and the EDU 31) executes a routine of FIG. 7 to estimate the substrate temperature. Specifically, as shown in FIG. 6, when the oil temperature is estimated while the cooling water temperature is higher than the predetermined value, a combustion temperature of the engine 11 is calculated using a map based on an operation condition such as rotation speed or load of the engine. Further, the increase of the oil temperature with respect to the cooling water temperature is calculated based on the combustion temperature. The base oil temperature is obtained by adding the increase of the oil temperature to the cooling water temperature, and the oil temperature is estimated by mathematically processing the base oil temperature.

[0064] In the second embodiment, 103 of FIG. 4 corresponding to the first embodiment is replaced with 103a, 103b of FIG. 7. The other processes are approximately the same as the first embodiment.

[0065] In FIG. 7, if it is determined that the cooling water temperature $CT$ is higher than the predetermined value $T1$ at 101, the combustion temperature is calculated at 103a using a map of the combustion temperature based on the engine operation condition such as engine rotation speed and load. The map of the combustion temperature is provided in advance based on experimental data and design data, and is stored in the ROM of the ECU 30. Furthermore, the combustion temperature may be corrected according to at least one of outside air temperature, intake air temperature, ignition timing, air-fuel ratio, valve timing, and so on.

[0066] Then, at 103b, the increase $\Delta T$ of the oil temperature with respect to the cooling water temperature is obtained using the combustion temperature, the last-time oil tempera-
ture OT(i−1) and a reflection rate ‘f’ based on a formula of
ΔT=[combustion temperature−OT(i−1)]×f.

Then, the base oil temperature BOT is obtained by adding the increase ΔT of the oil temperature to the cooling water temperature CT, at 104, and the present-time oil temperature OT(i) is estimated using the last-time oil temperature OT(i−1) and the correction coefficient “a” for the base oil temperature BOT at 105. The processes 103a, 103b, 104, 105 correspond to an oil temperature estimating portion 41 which is included in the ECU 30 or the EDU 31.

Then, the base substrate temperature BST is obtained at 106 using the present-time oil temperature OT(i), the last-time substrate temperature ST(i−1), the cooling water temperature CT, and the reflection rate “f”. Then, the present-time substrate temperature ST(i) is estimated at 107, by mathematically processing the base substrate temperature BST using the last-time substrate temperature ST(i−1), and the correction efficient “c”.

According to the second embodiment, when the oil temperature is estimated, the combustion temperature of the engine 11 is calculated based on an engine operation condition etc., and the increase of the oil temperature with respect to the cooling water temperature is calculated based on the combustion temperature. The base oil temperature is obtained by adding the increase of the oil temperature to the cooling water temperature, and the oil temperature is estimated by mathematically processing the base oil temperature. Therefore, the oil temperature can be more accurately estimated by considering the combustion temperature which is changed by the engine operation condition, and the substrate temperature can be more accurately estimated based on the oil temperature.

**Third Embodiment**

A third embodiment will be described with reference to FIGS. 8-10.

The ECU 30 (or the ECU 30 and the EDU 31) executes routines of FIGS. 9 and 10, so the substrate temperature is estimated in the same manner as the first embodiment. The MOS temperature is estimated based on the estimated substrate temperature, and the current limit control is conducted based on the estimated MOS temperature in which the MOS current is limited in a manner that the MOS temperature does not exceed the upper limit temperature.

Specifically, as shown in FIG. 8, while the temperature of cooling water CT of the engine 11 is higher than the predetermined value T1, the increase in the oil temperature with respect to the cooling water temperature is computed based on an operation condition such as rotation speed or load of the engine.

The base oil temperature is obtained by adding the increase in the oil temperature to the cooling water temperature, and the oil temperature is estimated by calculation mathematically processing the base oil temperature. The base substrate temperature is calculated based on the estimated oil temperature and the cooling water temperature, and the substrate temperature is estimated by calculation mathematically processing the base substrate temperature.

Further, an increase ΔMOST of the MOS temperature generated by self-heat-generation of the MOSFET 32 is calculated based on the MOS current, and the MOS temperature is estimated by adding the increase ΔMOST of the MOS temperature to the substrate temperature ST. Thus, the MOS temperature can be accurately estimated considering the self-heat-generation of the MOSFET 32.

At a timing t1 of FIG. 8, at which the estimated MOS temperature becomes higher than a predetermined upper determination value, the current limit control is executed, in which the MOS current is limited by a predetermined upper limit guard value in a manner that the MOS temperature does not exceed the permissible upper limit temperature. For example, the predetermined upper determination value is set to be slightly lower than the permissible upper limit temperature of the MOS temperature.

Thereafter, at a timing t2, at which the MOS temperature becomes lower than a predetermined lower determination value, the current limit control is finished by stopping the restriction of the MOS current. For example, the predetermined lower determination value is set to be lower than the predetermined upper determination value by a predetermined hysteresis.

The current limit control based on the MOS temperature according to the third embodiment is executed by the ECU 30 (or the ECU 30 and the EDU 31) based on routines of FIGS. 9 and 10. In the third embodiment, 301-307 of FIG. 9 are approximately the same as 101-107 of FIG. 4.

In FIG. 9, it is determined whether the cooling water temperature CT is higher than the predetermined value T1 at 301. If it is determined that the cooling water temperature CT is lower than or equal to the predetermined value T1 at 301, the estimation value of the oil temperature OT is set to be the same value as the cooling water temperature CT or a value provided by mathematically processing the cooling water temperature CT at 302.

If it is determined that the cooling water temperature CT is higher than the predetermined value T1 at 301, the increase ΔT of the oil temperature with respect to the cooling water temperature is calculated at 303, using a map based on the engine operation condition such as engine rotation speed and load. Furthermore, the increase ΔT of the oil temperature may be corrected according to at least one of outside air temperature, intake air temperature, ignition timing, air-fuel ratio, valve timing, and so on.

Then, the base oil temperature BOT is obtained by adding the increase ΔT of the oil temperature to the cooling water temperature CT, at 304. Then, the present-time oil temperature OT(i) is estimated using the last-time oil temperature OT(i−1) and the correction coefficient “a” for the base oil temperature BOT at 305.

Then, the base substrate temperature BST is obtained at 306 using the present-time oil temperature OT(i), the last-time substrate temperature ST(i−1), the cooling water temperature CT, and the reflection rate “f”. Then, the present-time substrate temperature ST(i) is estimated at 307, by mathematically processing the base substrate temperature BST using the last-time substrate temperature ST(i−1), and the correction coefficient “c”.

Thereafter, an increase ΔMOST of a base MOS temperature is obtained by multiplying the MOS current by a coefficient “d” which is a temperature increase ratio of the MOSFET 32 with respect to the MOS current, at 308 represented by a formula of ΔMOST=MOS current x d.

Thereafter, the present-time increase ΔMOST(i) of the base MOS temperature is obtained by mathematically processing the increase ΔMOST of the base MOS temperature using the last-time increase ΔMOST(i−1) of the base
MOS temperature and a correction coefficient "e", at 309 represented by a formula of $\Delta\text{MOST}(i) = \Delta\text{MOST}(i-1) \times e + \Delta\text{BMOST} \times (1-e)$.

[0084] Thereafter, the MOS temperature is estimated by adding the increase $\Delta\text{MOST}$ of the MOS temperature to the substrate temperature $ST$ at 310 represented by a formula of $\text{MOS temperature} = ST + \Delta\text{MOST}$. The processes 308, 309 correspond to a switching element temperature estimating portion 44 which is included in the ECU 30 or the EDU 31.

[0085] In the routine of FIG. 10, at 401, it is determined whether the estimated MOS temperature is higher than a predetermined upper determination value. For example, the upper determination value is set as a temperature slightly lower than the permissible upper limit temperature of the MOS temperature.

[0086] When it is determined that the estimated MOS temperature is lower than or equal to the predetermined upper determination value at 401, the routine of FIG. 10 is finished without performing the subsequent processes.

[0087] When it is determined that the estimated MOS temperature is higher than the predetermined upper determination value at 401, the current limit control is conducted at 402 to limit the MOS current with the predetermined upper limit guard value so that the MOS temperature does not exceed the permissible upper limit temperature. Furthermore, the MOS current may be limited by prohibiting the reference position learning.

[0088] Then, at 403, it is determined whether the MOS temperature is lower than a predetermined lower determination value. For example, the lower determination value is set as a temperature lower than the upper determination value by a predetermined hysteresis.

[0089] When it is determined that the MOS temperature is higher than or equal to the lower determination value at 403, the current limit control is continued by returning to 402.

[0090] Then, it is determined that the MOS temperature is lower than the lower determination value at 403, the current limit control is finished at 404 to stop the limiting of the MOS current.

[0091] According to the third embodiment, the MOS temperature is estimated based on the estimated substrate temperature. When the estimated MOS temperature becomes higher than the upper determination value, the current limit control is performed to limit the MOS current with the upper limit guard value so that the MOS temperature might not exceed the permissible upper limit temperature. Thus, the current limit control can be accurately conducted.

Fourth Embodiment

[0092] A fourth embodiment will be described with reference to FIGS. 11 and 12. The fourth embodiment may be a modification of the third embodiment.

[0093] The ECU 30 (or the ECU 30 and the EDU 31) executes a routine of FIG. 12 to estimate the MOS temperature. Specifically, as shown in FIG. 11, when the oil temperature is estimated while the cooling water temperature is higher than the predetermined value, a combustion temperature of the engine 11 is calculated using a map based on an operation condition such as rotation speed or load of the engine. Further, the increase of the oil temperature with respect to the cooling water temperature is calculated based on the combustion temperature. The base oil temperature is obtained by adding the increase of the oil temperature to the cooling water temperature, and the oil temperature is estimated by mathematically processing the base oil temperature.

[0094] In the fourth embodiment, 303 of FIG. 9 corresponding to the third embodiment is replaced with 303a, 303b of FIG. 12. The other processes are approximately the same as the third embodiment.

[0095] In FIG. 12, if it is determined that the cooling water temperature $CT$ is higher than the predetermined value $T1$ at 301, the combustion temperature is calculated at 303a using the map of the combustion temperature based on the engine operation condition such as engine rotation speed and load. Furthermore, the combustion temperature may be corrected according to at least one of outside air temperature, intake air temperature, ignition timing, air-fuel ratio, valve timing, and so on.

[0096] Then, the increase $\Delta T$ of the oil temperature with respect to the cooling water temperature is obtained using the combustion temperature, the last-time oil temperature $OT(i-1)$ and a reflection rate "i" at 303b represented by a formula of $\Delta T = \{\text{combustion temperature} - OT(i-1)\} \times f$.

[0097] Then, the base oil temperature $BOT$ is obtained by adding the increase $\Delta T$ of the oil temperature to the cooling water temperature $CT$, at 304, and the present-time oil temperature $OT(i)$ is estimated using the last-time oil temperature $OT(i-1)$ and the correction coefficient "a" for the base oil temperature $BOT$ at 305.

[0098] Then, the base substrate temperature $BST$ is obtained at 306 using the present-time oil temperature $OT(i)$, the last-time substrate temperature $ST(i-1)$, the cooling water temperature $CT$, and the reflection rate "b". Then, the present-time substrate temperature $ST(i)$ is estimated at 307, by mathematically processing the base substrate temperature $BST$ using the last-time substrate temperature $ST(i-1)$, and the correction coefficient "c".

[0099] Thereafter, an increase $\Delta\text{BMOST}$ of a base MOS temperature is obtained by multiplying the MOS current by a coefficient "d" which is a temperature increase ratio of the MOSFET 32 with respect to the MOS current, at 308.

[0100] Thereafter, the present-time increase $\Delta\text{MOST}(i)$ of the base MOS temperature is obtained by mathematically processing the increase $\Delta\text{BMOST}$ of the base MOS temperature using the last-time increase $\Delta\text{MOST}(i-1)$ of the base MOS temperature and the correction coefficient "e", at 309.

[0101] Thereafter, the MOS temperature is estimated by adding the increase $\Delta\text{MOST}$ of the MOS temperature to the substrate temperature $ST$ at 310.

[0102] According to the fourth embodiment, the oil temperature can be more accurately estimated by considering the combustion temperature which is changed by the engine operation condition, and the substrate temperature and the MOS temperature can be more accurately estimated based on the oil temperature, similarly to the second embodiment.

Other Embodiment

[0103] The present disclosure is not limited to be applied to the above system using the MOSFET 32 as a switching element which is operated to control the energization of the motor 26. Alternatively, the present disclosure may be applied to a control system using a field effect transistor (FET) such as transistor other than the MOSFET as the switching element.

[0104] Moreover, the present disclosure may be applied to a variable valve timing apparatus for an exhaust valve instead of the intake valve.
Furthermore, the phase variable mechanism of the variable valve timing apparatus is not limited to the above construction (FIG. 2), and may have other construction, while the variable valve timing apparatus controls the rotation phase of the camshaft with respect to the crankshaft by the motor.

Such changes and modifications are to be understood as being within the scope of the present disclosure as defined by the appended claims.

What is claimed is:

1. A control system for a variable valve timing apparatus that changes a valve timing of an internal combustion engine using a motor which is controlled by operating a switching element, the control system comprising:
   - an oil temperature estimating portion that estimates a temperature of lubricating oil of the internal combustion engine;
   - a substrate temperature estimating portion that estimates a temperature of a substrate to which the switching element is mounted based on the temperature of the lubricating oil estimated by the oil temperature estimating portion;
   - a current limit controller that limits a current flowing through the switching element based on the temperature of the substrate estimated by the substrate temperature estimating portion in a manner that a temperature of the switching element is restricted from exceeding a predetermined upper limit value.

2. The control system according to claim 1, wherein the current limit controller limits the current flowing through the switching element from exceeding a predetermined upper limit guard value when the temperature of the substrate estimated by the substrate temperature estimating portion becomes higher than a predetermined determination value.

3. The control system according to claim 1, further comprising:
   - a switching element temperature estimating portion that estimates the temperature of the switching element based on the temperature of the substrate estimated by the substrate temperature estimating portion, wherein the current limit controller limits the current flowing through the switching element from exceeding a predetermined upper limit guard value when the temperature of the switching element estimated by the switching element temperature estimating portion becomes higher than a predetermined determination value.

4. The control system according to claim 3, wherein the switching element temperature estimating portion computes an increase of the temperature of the switching element, which is caused by self-heat-generation of the switching element, based on the current flowing through the switching element, and the switching element temperature estimating portion computes the temperature of the switching element by adding the increase of the temperature of the switching element to the temperature of the substrate estimated by the substrate temperature estimating portion.

5. The control system according to claim 1, wherein the substrate temperature estimating portion computes a base temperature for the temperature of the substrate based on the temperature of the lubricating oil estimated by the oil temperature estimating portion and a temperature of cooling water of the internal combustion engine, and the substrate temperature estimating portion computes the temperature of the substrate by mathematically processing the base temperature for the temperature of the substrate.

6. The control system according to claim 1, wherein the oil temperature estimating portion computes an increase of the temperature of the lubricating oil with respect to a temperature of cooling water of the internal combustion engine, the oil temperature estimating portion computes the temperature of the lubricating oil by mathematically processing a value calculated by adding the increase of the temperature of the lubricating oil to the temperature of cooling water.

7. The control system according to claim 1, wherein the oil temperature estimating portion computes a combustion temperature of the internal combustion engine based on an operational status of the internal combustion engine, the oil temperature estimating portion computes an increase of the temperature of the lubricating oil with respect to a temperature of cooling water of the internal combustion engine based on the combustion temperature, and the oil temperature estimating portion computes the temperature of the lubricating oil by mathematically processing a value calculated by adding the increase of the temperature of the lubricating oil to the temperature of cooling water.